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Age Related Changes in Cognition During the Working Years

Earl Hunt and Christopher Hertzog
University of Washington

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In order to alleviate present and anticipated personnel shortages, the Armed Services will have to move away from the present reliance on young adults as a source of personnel. The impact will be heaviest on the technologically oriented services, such as the Navy. Previous analyses have indicated that adults in the normal working years (20-60) can meet the physical requirements of most service occupations. Questions remain about the effects of age changes in cognition on work performance of older personnel.

Changes in cognitive capacities over the adult working years are reviewed -

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) here. Two major decrements are noted; a general deterioration of sensory functioning and a slowing of higher cognitive processes. The latter slowing may be sufficient to affect performance in situations in which time demands on responding are on the order of fractions of seconds, but would probably not affect most work situations. The general effects of experience, combined with an increase in verbal intelligence throughout the working years, argues for increased competence of older individuals in many work situations. There are indications that spatial reasoning abilities and the ability to develop solutions to new problems ("fluid intelligence") decrease with age. Secondary and review articles may overstate this effect. The primary studies themselves have serious design flaws. The best designed studies indicate that the drops do occur, but that the effect may not begin to be serious until the middle 50s or beyond. Because of problems in design and/or choice of performance measure, this topic requires further exploration.

The above statements refer to general trends. Very wide individual differences are found. Although the relative order of individuals on tests of mental competence remains remarkably constant over adult life, the absolute difference between people increases. In practice, this means that as people age, those people who initially had high levels of ability retain them, while people with initially low levels of performance get worse. This finding further emphasizes the importance of obtaining recruits who are of average or above average ability as young adults. It also suggests that high ability personnel in the 40-60 age range may be preferable to younger personnel of low ability, especially given technical experience.

General physical health is related to the maintenance of cognitive performance throughout adult life. In particular, indications of cardiovascular problems (hypertension, heart diseases, minor strokes) are usually accompanied by slowing of performance in cognitive tasks. There are indications that immoderate use of alcohol can produce substantial loss in cognitive performance, probably on a permanent basis. The evidence is quite clear that this happens if alcohol use is carried to the point of frequent severe intoxication. The evidence is less clear if use is limited to frequent social drinking, but there is a distinct possibility that this is a cause of loss of cognitive functioning in adults. Losses in sensory capacity, particularly audition, are exacerbated by environmental hazards.

Standard medical examination procedures for sensory functioning (e.g., visual acuity charts) appear to underestimate the functional loss suffered by an individual in demanding work situations. New human engineering standards may be appropriate for work stations that are to be operated by people in their 40s and 50s, in order to accomodate for sensory deterioration. Medical and psychological research should be initiated to develop indices of an individual's functional age by individual differences in physical health (especially cardiovascular problems) and health-related behaviors (exercise, alcohol and substance abuse, etc.). The goal would be the development of a reliable medical and psychological screening procedure to identify older personnel at risk for performance decline. A study should be initiated of long term changes in performance with age in service relevant populations. The Reserve forces are suggested as an appropriate population. This study is needed because of the questionable relevance of some of the tests used in the literature as indicators of performance in military work situations, and because previous studies have indicated that different aging trends may be found in different populations.

Age Related Changes in Cognition During the Working Years

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The preparation of this report was motivated by a simple, practical question. Some years ago Dr. Henry Halff, of the Office of Naval Research, gave a colloquium at the University of Washington in which he discussed psychological problems faced by the modern military. One of the problems that he mentioned was the problem of obtaining enough "young and vigorous" enlistees, and retaining them long enough so that they returned the training investment to the services. This piqued the curiousity of one of us (EH), who began to read in the area, and to talk with CH, who had his graduate training in the Psychology of Aging. The demographic problem was clearcut: the Defense Department, and more generally U.S. industry as a whole, must come to grips with a simple demographic fact. The age distribution of our population is going to change markedly over the next twenty to thirty years. Modern industries, including but certainly not limited to the Defense Department, use people as information processing devices more than they use them as sources of power. We wondered whether or not there were age-related changes in cognition that would force changes in industrial practice.

When we turned to the literature for guidance, we quickly discovered that the literature simply was not organized to answer our question. There were two reasons. Most of the research on "gerontological psychology" is motivated by a desire to understand the life changes associated with old age. Work in the field is also strongly oriented toward the study of cognitive changes that might produce a problem for an (elderly) individual in his or her daily life. These two orientations are reasonable. Much of the research in this field is funded by an agency (The National Institute on Aging) that is specifically charged with consideration of the problems of the elderly. The scientists who work on problems of aging have a strong institutional and personal commitment toward doing something for treatment of these individuals. For our purposes, though, these two orientations were somewhat unfortunate. We wanted to know something about changes in cognition that occurred during the normal working years. Such changes would probably be small, and wuld affect an individual only gradually. From the point of view of an epidemiologist or economist, however, small changes in individuals might mean major changes in the effectiveness of a work force.

We concluded that a survey was required, directed at the specific questions that we wished to have answered. With the encouragement of Dr. Halff and Dr. Marshall Farr of the Office of Naval Research, we spent a substantial amount of time reviewing the literature and asking psychologists and physicians what they know about "middle aging". In addition, we have also visited various industrial and Naval establishments, in order to get a better picture of current personnel practices. Our hope was that we would then be able to make a better guess about how the changes in people that the scientists saw as possibly affecting the way that a particular high technology organization, the U.S. Navy, had to do its business.

Naturally none of the people who generously gave their time are responsible for our conclusions. We only hope that upon reading this report, they do not regret having talked with us! We would like to thank the following people, who have provided most useful assistance, data, and best of all, constructive criticism of our efforts:

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Earl Hunt

Christopher Hertzog

Aging and Cognition

1. INTRODUCTORY REMARKS

Since World War II the United States has drawn its military manpower from post adolescents and young adults. The typical career pattern for a soldier, sailor, marine, or airman has been to enlist in the late teens or early twenties and serve for a single enlistment period. In order to obtain the skilled technicians that the modern military needs special efforts are made to retain and train a cadre of professional specialists who serve for longer periods of time. It is well known that this system of recruitment is not working satisfactorily today and that, given inevitable demographic changes, the problem is likely to be worse in the near future. The services must find some way to enlist and retain more experienced technicians, both in the commissioned and non-commissioned ranks.

Two courses of action are possible. The services could attempt to improve their retention rates, which are presently quite low, while continuing to train specialists themselves. This will be called the "retention option." In addition, programs could be initiated to enlist older persons, who are already skilled, to fill technical positions. Direct recruitment of skilled people is done now for a few military occupations, noticeably medicine, and was a widespread practice in the 19th century. The option of recruiting directly into the higher ranks will be called the "lateral entry" option. It is likely that both options will be taken, because our national policies demand a strong military force. Either option is certain to have one result; the average age of servicemen and women will increase. Will this mean a military with reduced vigor or greater skill? What is the tradeoff between these possibilities? This report examines one aspect of the problem; the liklihood of changes in the cognitive capacities of older personnel, here defined as individuals ranging in age from 20 to 60.

There would be no real reason for the military to be interested in investigating cognitive changes in adults if age changes in the military population were expected to be small. On the contrary, we believe that substantial "aging" of the miltary force is likely. This is partly because of the extreme youth of the present active duty force. In 1977 only 12% of active duty male enlisted personnel were over 35 and only 1% were over 45. The comparable figures for the civilian work force were 52% and 33%. When the retention problem is solved the Armed Forces population can be expected to move toward but not reach the age distribution of the civilian work force. A reasonable estimate of the eventual military age distribution can be obtained by looking at the present Reserve forces. These were the people who "almost" made the military a career. As of the end of 1980, 33% of Naval Reserve enlisted personnel and 62% of Reserve officers were over the age of 35 (U.S. Naval Reserve; Reserve Manpower, Mobilization

Planning, and Policy Division, Notes 1 and 2). It thus seems reasonable to suppose that the number of active duty personnel over age 35 will at least double if lateral entry and retention attempts are successful.

A related issue is how the older personnel will be used. Major changes from current practice can be expected. At present, and in the immediate past, older, more experienced individuals have been assigned to supervisory roles. This tradition will have to be modified. It will make more sense to retain experienced people in those positions where their experience is relevant. This means that individuals who actually operate equipment will be older than they are now, although not "old" in the usual sense. Put succinctly, there is no proposal to employ 55 year old infantrymen, but 40 year old tank drivers are a distinct possibility.

Economic analyses of the use of older personnel in military roles have generally been encouraging (Binikin and Kyriakopolous, 1979; Parker, Christensen, and Every, 1978). It has been pointed out that more mature servicemen are better motivated and more reliable. Surveys have shown that there are relatively few service occupations that make physical demands beyond those that can be met by a reasonably healthy forty year old man, and most of the normal physical demands encountered in service life could be handled by people in their fifties. The economic analyses of which we are aware, however, do not appear to have considered the possibility that there are important changes in cognitive capabilities from age 20 to age 60. The issue is a complex one. Foreshadowing our conclusion, it is fairly easy to demonstrate declines in cognitive performance over the working years, if one chooses the right tasks. Conversely, it is also fairly easy to demonstrate increased cognitive performance over the same age, by a different choice of tasks. To complicate the matter further, within any age group there are wide individual differences. These increase with age. On almost any measure of cognitive performance the difference between two randomly chosen forty year olds is likely to be greater than the difference between two randomly chosen twenty year olds. Furthermore, the services are rightly concerned with performance, not potential. In general older personnel have more experience on the job and have made more stable social adjustments than have young adults. These positive aspects of "middle aging" often translate into more efficient performance, with dramatically reduced requirements for supervision. In the normal individual the positive aspects of maturity almost certainly overwhelm any minor effects of deterioration, at least up to age 35. Beyond that age some cognitive changes occur, in some individuals, that may present problems in some occupations. All these qualifiers should be kept in mind in evaluating the data reported in the remainder of this report.

The report itself is organized into three sections. Each section reviews different empirical findings concerning age related changes in cognition during the working years; arbitrarily defined as the period from age 25 to age 55. Section 2 raises some general issues about the studies of aging. Section 3 describes what has been learned by psychometric studies, in which people of varying ages are given different forms of intelligence tests. This data provides a useful broad view of intellectual change. The following sections describe more limited studies of human information processing, conducted within the tradition of experimental psychology. The topics covered are sensory function, the ability to maintain attention, response selection, speeded decision making, accuracy of retention of information in memory, and problem solving. A general critique of work in the field is included.

The last section of the report deals with possible actions by the Armed Services. These fall into two headings; modifications of present practice, and the initiation of programs of research.

2. THEORETICAL AND METHODOLOGICAL ISSUES

The study of aging involves more than calculating the correlation coefficient between chronological age and performance measures. This section presents several ideas which are of central importance in understanding and evaluating the literature.

MODELS OF AGING

The simplest view of adult aging is that it represents inevitable biological deterioration. This will be called the biological decrement model. It characterizes change from young adulthood to old age as a decline from peak capacity to progressively lower levels of performance. The decline is assumed to be due to the biological aging process. Reductions in physiological functioning lead in turn to reductions in cognitive performance. The model certainly captures some of the truth about aging, but overall it is a gross simplification of the facts. The rate of biological aging varies considerably between individuals, so that an individual's "biological age," is often poorly estimated by chronological age. Moreover, within an individual, biological subsystems may age at widely varying rates. Thus any statement about general biological trends, let alone their cognitive consequences, may be quite inaccurate when applied to an individual.

A second limitation of the biological decrement model is that it may lead to oversimplified interpretations of the effects of aging upon cognitive behavior in a work environment. We shall repeatedly stress tradeoffs between decrements in maximum capacity due to age and increases in efficiency of performance due to experience. The need to consider experience is particularly important where an "elementary" cognitive process has been isolated by means of complex experimental techniques. Even if age deficits in this process are found in the experimental laboratory, we must still judge whether these deficits will limit the performance of an experienced person in familiar working situations.

The processes of biological aging are statistically related to, but areconceptually distinct from many pathological processes which are correlated with chronological age. Cancer, arteriosclerosis, diabetes, and arthritis are examples of age-correlated pathologies which are not inevitably associated with the aging process, although their incidence increases with increasing age. Some age-correlated diseases, especially cerebrovascular disease, hypertension, hormonal dysfunction, etc., have deleterious cognitive effects. Certain behaviors (e.g., alcohol and drug abuse) may lead to poor health and abnormal physiological and cognitive decline. In this review, we take the position that normal aging changes must be distinguished from pathological aging changes. Admittedly, the distinction can be somewhat arbitrary -- today's "normal aging" might be tomorrow's pathology after discovery of a new disease process. However, the distinction remains important. Many of the apparent effects of aging may be modified by personal health practices or by aggressive environmental and occupational safety programs. In considering the industrial implications of an aging work force, it is obviously important to distinguish between inevitable and modifiable changes in worker characteristics.

Because we are concerned with industrial effects, we generally shall not discuss changes in cognition that have been found in the elderly, i.e. people beyond the normal retirement age. By contrast, most of the literature on aging has concentrated on the elderly, arbitrarily those past 60. This is an important distinction, because organic problems, including senile dementias, begin to account for more and more of the variance in cognitive behavior as people reach great age. Thus the literature on the elderly may stress a biological model that is appropriate for one age period, but quite inappropriate for another. We note that this does not always mean that biological models apply only to the elderly. Because people in the work force generally face more demanding information processing tasks, a biological deficit that could be ignored by a retired person might be limiting to a person employed in a taxing situation.

Our concentration on the working years presented us with a problem in reviewing the aging literature. There are relatively few studies that examine the 25-60 age interval. The modal study of aging is a two group comparison: young adults (often 18-20 year old students) versus old adults (often 65-75 year old retirees). Such comparisons are not merely poorly suited to our purposes --

they are also often of questionable methodological validity. Thus we have deliberately excluded many old/young comparison studies from this review, keeping only those that offer a potentially important insight into aging effects on cognition, or those that cover a cognitive change likely to be important over the adult working years. For basically the same reason we shall not discuss studies of pathological aging, such as Alzheimer's disease or Huntington's Chorea.

METHODOLOGICAL CONSIDERATIONS

Most studies of adult aging utilize a cross-sectional design, in which people of different ages are compared at the same point in time. In order to infer that group differences in performance are due to group differences in age one must assume that the groups tested are otherwise comparable. It is extremely difficult to do this, because different selection factors operate when one recruits participants from different age groups. Lachman, Lachman, and Taylor (1981) examined several relevant journals, and concluded that about 80% of the reports that are published failed to pay sufficient attention to this issue. Largely because of this problem, one must be concerned about the replicability of cross-sectional studies when evaluating the literature. While it is probably impossible to control for all possible confounds with age in any one study, different studies will have different biases. Age effects can then be discerned by detecting consistencies in the results from several independent experiments.

Longitudinal studies of aging follow a panel of participants for an extended length of time. Intuitively, this is a more valid way to establish age trends. Longitudinal studies, though, also have practical and theoretical limitations. The greatest practical limitation is the expense of recruiting and maintaining a sample. Another serious issue is how representative the sample is of the general population. It is difficult to obtain a sample of "typical people" to participate in a study that extends for years. Longitudinal studies have tended to be biased toward the use of upper-middle class subjects, who are socially and geographically more stable, or to the use of panels recruited from people who deal with a specific institution, such as the Veterans' Administration. The problem of subject selection occurs both in initial recruitment and, more seriously, in the stage of follow-up testing. People who remain in panels tend to be those who are, on the average, better socially adjusted, healthier, and more cognitively competent. As a result, longitudinal studies present a more benign picture of aging than is obtained from cross-sectional studies.

The use of young/old designs (or more extended cross-sectional sampling) has led to the general use of analysis of variance techniques to judge the statistical significance of age differences. We have observed two problems which have been consistently associated with this approach: acceptance of the null hypothesis (no age changes), and reference to the proportion of age-predicted variance. It is sometimes the case that a study will fail to reject the null hypothesis of no age differences, and will then conlude that "there are no age changes until age X." Such a statement is not warranted unless the investigator also evaluates the power of the statistical comparison. Surprisingly, this simple statistical fact is frequently ignored both in the primary and secondary literature.

A slightly different problem of interpretation arises when an investigator finds that the age effect only accounts for a small proportion of variance, and then concludes that "age effects are reliable but small, and are probably not of great practical importance." Practical importance is something that cannot be defined in general, it must be defined in terms of the costs and benefits in a specific situation. A decrement in choice reaction time that would be trivial to a retired banker might be cause for retiring an airplane pilot. Our feeling is that most workers in gerontology, who understandably are strongly oriented toward dealing with the problems of the elderly, interpret "practical" as meaning "has a notable effect on the individual's lifestyle." Changes in performance that are not practically important, in this sense, can be extremely important from the point of view of a large employer, such as the Armed Services. Loosely, the difference is between the viewpoint of a particular individual, who might be calculating the chances of an accident happening to them, compared to the viewpoint of an employer, who must calculate the expected number of accidents in an organization employing literally millions of people. For brevity, we shall refer to these different viewpoints as a concern for "clinical" and "industrial" effects. Small changes in cognitive performance will be discussed whenever it appears that they might have effects at the industrial level. Such an effect might well be disregarded at the clinical level.

In many reports age effects are evaluated by asking whether or not one age group is "statistically different" from another along some dimension of performance. It is generally more fruitful to discuss trends, rather than comparisons between specific groups. To do this one must fit some kind of decremental curve (linear, exponential, etc.) to the group means for different age groups. Age curve fitting is helpful in asking whether average age changes appear to have begun prior some age, or in estimating the average rate of change. There are several limitations of this type of fitting, however. Curves of this kind may give an average "developmental curve" which does not accurately reflect the true aging curve of any given individual. Fitting the means ignores the individual variability about the means. A good fit of a curve function to the observed means does not imply that there are no individual differences in aging rates.

Finally, similarity in aging curves between different cognitive processes in no way implies a common causal mechanism, and should not be so interpreted. Even given these limitations, we shall find age curve fitting to be a useful way of summarizing many cognitive effects of aging during the working years.

COHORT EFFECTS

Our last methodological point deals with a moderately subtle issue that has introduced a confounding into easily 95% of all studies of aging. This is the "cohort effect," which was first discussed in detail by Schaie (1965). A cohort is, for our purposes, a group of people who join a population of interest at a particular time. Examples would be all people born in 1903, or all people entering the Marines in 1967. Cohort effects are effects on performance that are specific to a particular cohort. Suppose, as is reasonable, that one's adult verbal skills are determined largely by habits acquired during the school years. Suppose further that the length and effectiveness of schooling increased steadily from 1920 until 1950. A cross-sectional study of verbal intelligence, conducted in 1975 might have revealed an "age related decline" in verbal performance that was actually due to the older subjects having received less effective schooling, rather than being due to age itself. The problem is that in the cross-sectional design any cohort effects are completely confounded with age effects. One can even think of situations in which a cohort effect would produce a "negative age effect." Continuing the example, suppose further that the effectiveness of public education has dropped from 1950 to 1980. (Indeed, many observers have claimed that it has.) If so, and if school acquired verbal habits are maintained throughout adult life, a "negative age effect" should appear in a cross-sectional study conducted in the year 2000.

Longitudinal studies, being studies of a particular cohort, do not confound age and cohort effects. The findings of a longitudinal study, however, are statistically only generalizable to the cohort studied.

There are complicated designs that can be used to evaluate cohort and age effects separately (Schaie,1965, 1977). Essentially these designs involve the conduct of repeated cross-sectional designs, over a period of years. Thus the cohorts born in 1940, 1950, and 1960 might be sampled in 1980, 1990, and 2000. Combined longitudinal and cross-sectional designs do solve the logical problem of confounded age and cohort effects. The problem with these designs is that they are so expensive that they can seldom be utilized.

Cohort effects are of particular importance in the study of aging over the working years, because there are marked cohort effects in industrial settings. The military services afford a good example. Which members of a cohort join the military depends upon the social conditions prevailing at the time that cohort enters the normal military recruitment age. In particular, changes from war to peace and the introduction of an all volunteer service have markedly affected military recruitment in the past twenty years. The sort of cohort effects that one would expect from these social changes probably interact with aging effects. People with high levels of ability as young adults have generally been found to be more resistant to the effects of age on cognition. There is a well documented trend toward the enlistment of more and more individuals of lower mental categories (as measured by the Armed Forces Qualification Test), at least since 1975. If we combine these two facts, we are forced to predict that those servicemen and women who were recruited in 1980 will, on the whole, not provide as high a percentage of qualified senior personnel, fifteen or twenty years hence, as did the cohorts recruited in the 1950s and 1960s when they reached their thirties and forties.

CONCLUDING COMMENTS

Recounting all the possible design flaws that can afflict research studies can have a deadening effect. This is true of any field. One simply cannot throw up one's hands and say "Nothing can be learned." Human aging is a natural phenomenon that will never be studied in a controlled laboratory environment. The ideal experimental design is impossible to achieve. The concept of aging is itself nebulous. To what extent should one be concerned only with the aging process itself, and to what extent should one be concerned with life events that are not aging, but that are statistically associated with age? In the following sections we shall review many studies. None of them will unequivocally determine how cognition changes from 20 to 60. Taken together, they present a coherent picture.

3. PSYCHOMETRICS

GENERAL

This section reviews the literature on age changes in intelligence, as measured by traditional psychometric tests. The "psychometric" literature is typically contrasted to the "experimental" literature, which reports the investigation of cognition by classic experimental methods. This sort of division of knowledge is a taxonomy by method of investigation, rather than a taxonomy by content. It is necessary because differences in methodology have lead to differences in theory.

Although the term "psychometric methods" has come to connote group administration of paper and pencil tests of knowledge, reasoning, and other cognitive skills, the term originally implied the application of classical measurement theory to the study of cognition (Nunally, 1978). Psychometric methods were developed so that individual differences in knowledge and thinking could be measured reliably by a standard set of criteria. Although many "psychometrists" explicitly recognized that an understanding of basic cognitive processes would require a synthesis of information gathered from the paper and pencil tests with data collected by other measurement methods (Thurstone, 1944), the psychometrists and experimental psychologists have gone their separate ways until fairly recently (Carroll and Maxwell, 1979; Cronbach, 1957).

Comparing the two kinds of studies can be confusing, because of specialized methods and terminology. In experimental psychology two mental processes are distinguished from each other by showing that different experimental manipulations produce different effects. If the manipulation of certain stimulus characteristics affects one aspect of task performance, but not the other this is taking as evidence for different processes underlying the two performances. The same logic is used in psychometric studies of intelligence, but the experimental variable is the identity of the individuals tested. Suppose, as is the case, that verbal problems are hard for some people, while spatial problems are hard for others. Therefore there must be distinct processes underlying verbal and spatial problem solving.

Although the logic underlying experimental and psychometric psychology is similar, the manipulations that are feasible and the data analyses methods that are used can be quite different. As a result, the two technologies cannot always be used study the same cognitive processes. It is hard to imagine a paper and pencil test of the speed of visual perception. It is equally hard to imagine a two hundred person correlational study of psychophysical effects. On the other hand, where the technologies can be used to attack the same problem, they are basically studying the same topic. Therefore, it should not be surprising if the conclusions drawn from psychometric studies of "intelligence" parallel conclusions from experimental studies about "cognitive processes". Indeed, one can regard a comparison of conclusions drawn about aging and its effects upon cognition as a rough check on the validity of each method.

Compared to the experimental technology, the psychometric technology has both a marked advantage and a marked disadvantage. The advantage is that testing procedures may be used with much larger samples. The large sample reduces the likelihood of obtaining an age effect because of unusual performance by a few individuals. It also makes it possible to exercise a great deal more control over population variables that may be confounded with age. This is in marked contrast to many experimental studies, in which investigators have all too often abandoned any pretense to representative sampling from different age groups, and thus have committed the confoundings that were discussed in the comments made above concerning cross-sectional designs. In contrast, there are at least some psychometric studies that have attended carefully to the definition of the population to be studied, and to the use of a consistent sampling method from different age groups within that population. Furthermore, the psychometric literature is not solely dependent upon cross-sectional studies for inferences on age effects. Longitudinal studies are more common in psychometric than in experimental psychology. On occasion psychometric studies have used sophisticated combinations of cross-sectional and longitudinal designs, and these have proven informative. Were these methods to be applied to experimental studies, the cost would generally be prohibitive.

The disadvantage of the psychometric method is that the behavior recorded is usually a gross one, the total number of items correct on a particular test. Such a summarization loses a great deal of information about the cognitive processes that are applied to solve different problems within a test. Consider a commonly used psychometric for measuring spatial ability. People are asked to compare rotated figures to some comparison figure, and to determine whether the figures are identical. The test typically includes several different figures, often a different one for each item. A person's score is determined by the total number of items completed in a fixed time period. It has been found that older people complete fewer items than younger ones. The age difference in performance might reflect an increase in the time needed to rotate and compare the figures inside the head, or it might reflect an inability to visualize a rotation altogether for some figures. Age differences might be largest for certain types of figures. While sophisticated item analyses can be used to investigate these issues, usually no such investigation is made. The information needed is usually lost in the process of calculating the total number of correct item responses. However, as we shall see below, experimental models and techniques make it possible to determine the locus of individual differences in spatial rotation of images more precisely.

More generally, when we compare psychometric to experimental data we often find that, although the nature of the defining difference between groups (e.g., young vs. old) is likely to be more clearly stated in a psychometric study, the theoretical explanation of the dependent variable is often more speculative. Since the advantages of the one technology are the disadvantages of the other, perhaps the most enlightening findings are those in which the psychometric and experimental conclusions complement each other.

THE CLASSIC AGING PATTERN

Cross-sectional studies of intelligence have repeatedly produced results that Botwinick (1977) has referred to as the

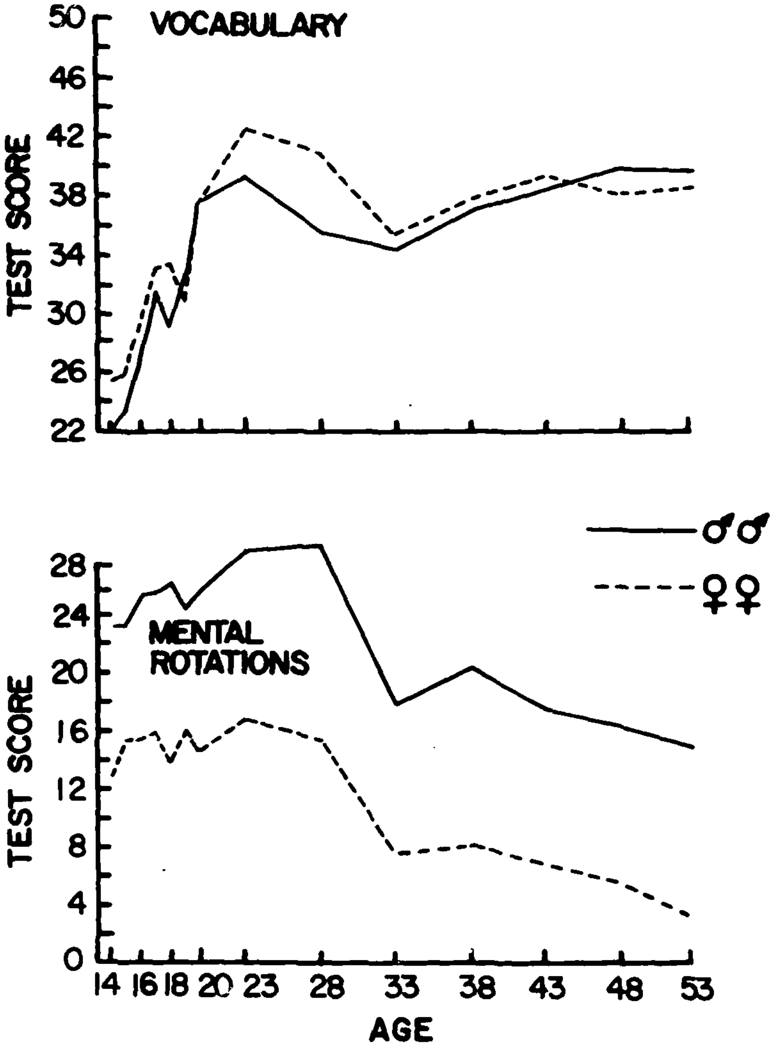


Figure 1. Changes in Vocabulary Test and Test of the ability to rotate and compare figures "inside the head." Data from cross sectional survey of Hawaiian residents. (Wilson et. al., 1975).

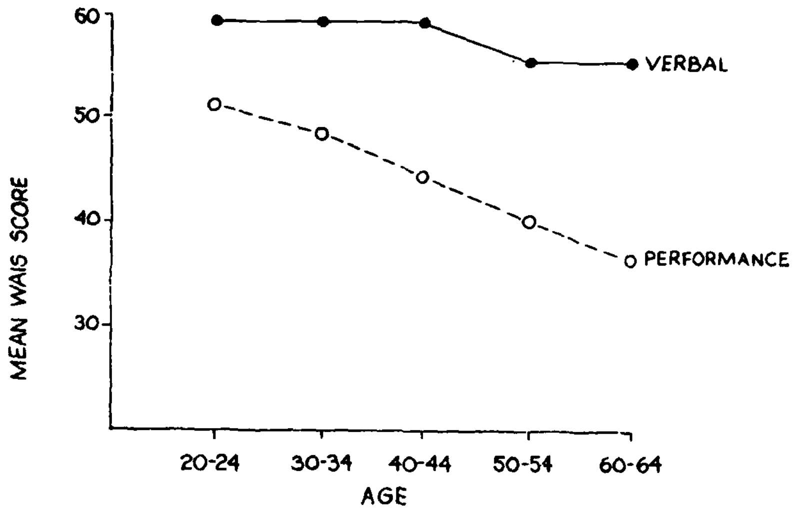


Figure 2. Wechsler Adult Intelligence Scale (WAIS) I.Q. scores as a function of age. From data presented by Matarazzo, 1972).

"classic aging pattern." Performance on tests of verbal ability shows little change from 20-60, and may even increase,. Non-verbal skills decline with age. The classic pattern is illustrated in Figure 1, which shows the results from a large cross-sectional study. The test battery included a standard vocabulary test and a paper and pencil measure of spatial rotation. The spatial test asked individuals to compare pairs of three-dimensional figures, composed of groups of cubic blocks. The two figures were either identical or mirror-images, rotated to different orientations. Individuals are asked to compare the two figures and determine whether they are identical or mirror-images. As Figure 1 shows, there was are large age differences in the spatial measure but not in the vocabulary test. A similar picture has been obtained in studies using traditional intelligence tests, such as the Wechsler Adult Intelligence Test (WAIS). Figure 2 shows the WAIS norms across ages for WAIS Verbal and Performance scales (Matarazzo, 1972). Note that the Performance subscale shows cross-sectional age differences from roughly age 30 onward, while the Verbal subtest does not. Indeed, Wechsler labeled his Verbal subtests "Hold" tests, and his Performance subtests "Don't Hold" tests, precisely because of the cross-sectional effects shown in Figure 2.

The WAIS subtests are sometimes criticized within the psychometric literature for being "factorially complex" -- meaning that they measure multiple kinds of intelligence. For many purposes it is more useful to consider performance on cognitive traits that are more elementary than global measures of verbal and non-verbal intelligence. Such traits are sometimes called "Primary Abilities" (Thurstone, 1938). This complexity could distort underlying age differences in more basic levels of intelligence if the age differences were not consistent for different kinds of intelligence. A prototypical primary ability theory may be found in a review by Horn (1978), who argues that roughly some 30 primary abilities have been reliably demonstrated. This coincides with the conclusion of several other workers. The Educational Testing Service's widely used Reference Kit for Primary Mental Abilities now contains 23 separate tests (Ekstrom, French, and Harman, 1976). Horn, and several other theorists, have concluded that some of he abilities are arranged hierarchially, with more primitive traits contributing to global ones, such as "verbal intelligence."

Cross-sectional studies have reported age differences on several primary abilities. Spatial orientation and inductive reasoning seem to be particularly susceptible to age effects (Schaie, 1959). Other studies have reported cross-sectional age differences on measures of perceptual speed and flexibility. For example, Lee and Pollack (1978) reported sizable cross-sectional declines in performance on the Embedded Figures Test, which requires individuals to detect a figure embedded within a concealing context. The results of studies using tests of specific primary abilities generally conform to the the classic aging pattern: tests of reasoning, problem solving, spatial visualization, and the like show greater cross-sectional age differences than measures of vocabulary and verbal fluency (Botwinick, 1977).

Conclusions drawn on the basis of average data must be qualified by considering individual variation about the average. There are large individual differences in psychometric test performance among adults over the working years. This will be a recurring theme throughout our report. Figures 3 and 4 chart cross-sectional age effects on the Raven's Progressive Matrices test, a widely used test of nonverbal reasoning, and the Elithorn Mazes, a measure of spatial problem solving (Heron and Chown, 1967). Raven's test is of particular interest, since it is considered one of the better measures of inductive reasoning ability. Individuals examine a sequence of pictures to discover the sequential pattern of pictures, and then induce what the pattern of a missing picture should be. Figure 3 shows that average performance on the Raven declines with increasing age, beginning during the 30's. However, the plot of individual data show the large range of individual differences in Raven performance at different ages. Note that, in general, the spread of individual differences is large relative to the mean performance levels within each age group. In fact, some of the highest scores in the sample were obtained by subjects in their 60's and older. Figure 4 shows that this type of effect is by no means specific to the Raven -- the large individual differences are found for Elithorn Mazes as well. The individual differences observed on test performance are not random, they are reliably related to other characteristics of the individual. This topic will be covered in more detail in a subsequent section.

The classic aging pattern represents the typical results of cross-sectional studies. Longitudinal studies, which follow individuals over a period of years, show much less decline in nonverbal measures of intelligence. Indeed, the longitudinal data suggests that the decline occurs in the 60's or later, and is not consistently found for all individuals. Longitudinal decline, where it is observed, is apparently often associated with declines in physical health (Baltes and Labouvie, 1973; Jarvik, Eisdorfer, and Blum, 1974; Jones, 1959).

COHORT EFFECTS AS MODIFIERS OF THE CLASSIC PATTERN

In the section on methodology it was pointed out that cohort effects could, in theory, distort the pattern of age effects. Such effects do exist, and if not considered, may lead to an overestimation of the size of age effects. This has been shown by a series of studies conducted by K.W. Schaie and his colleagues (Schaie, 1979). These experiments represent perhaps the best designed study of aging that is in the literature. Basically, Schaie's group conducted a combined longitudinal and cross-sectional study of members of a group health plan.

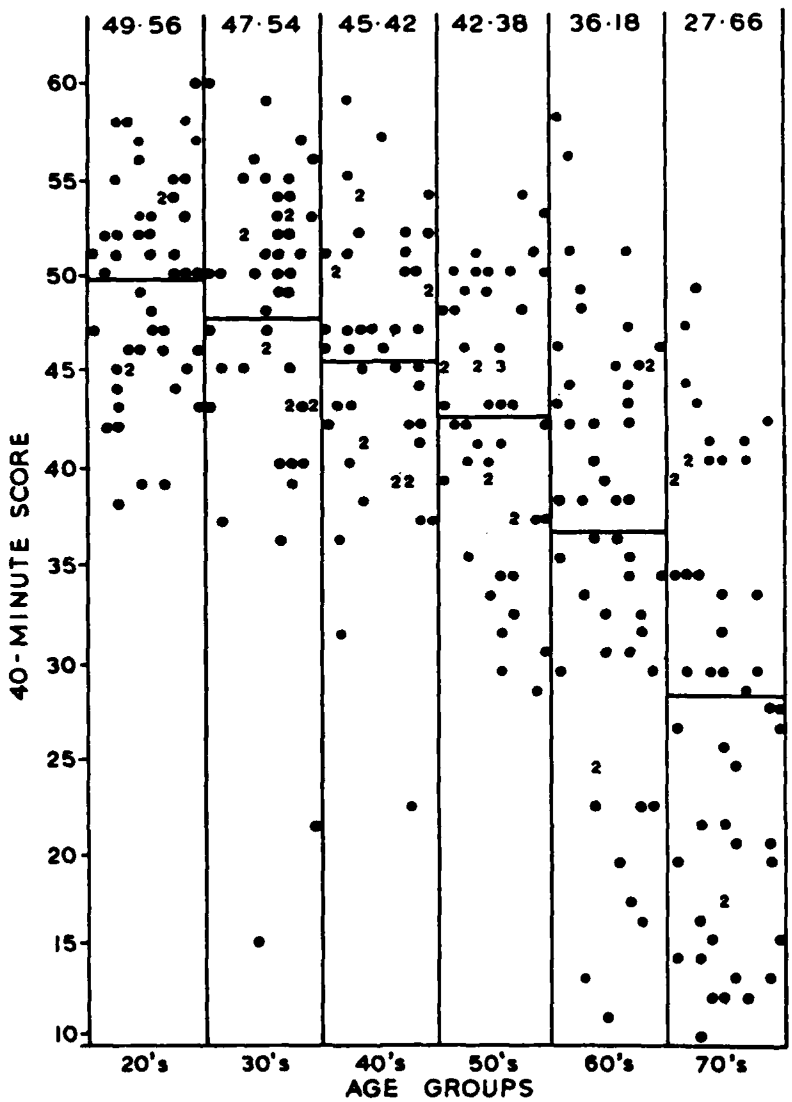


Figure 3. Score (Number correct in 40 minutes) on Raven's Progressive Matrix Test. Distributions for various ages. (Heron and Chown, 1967).

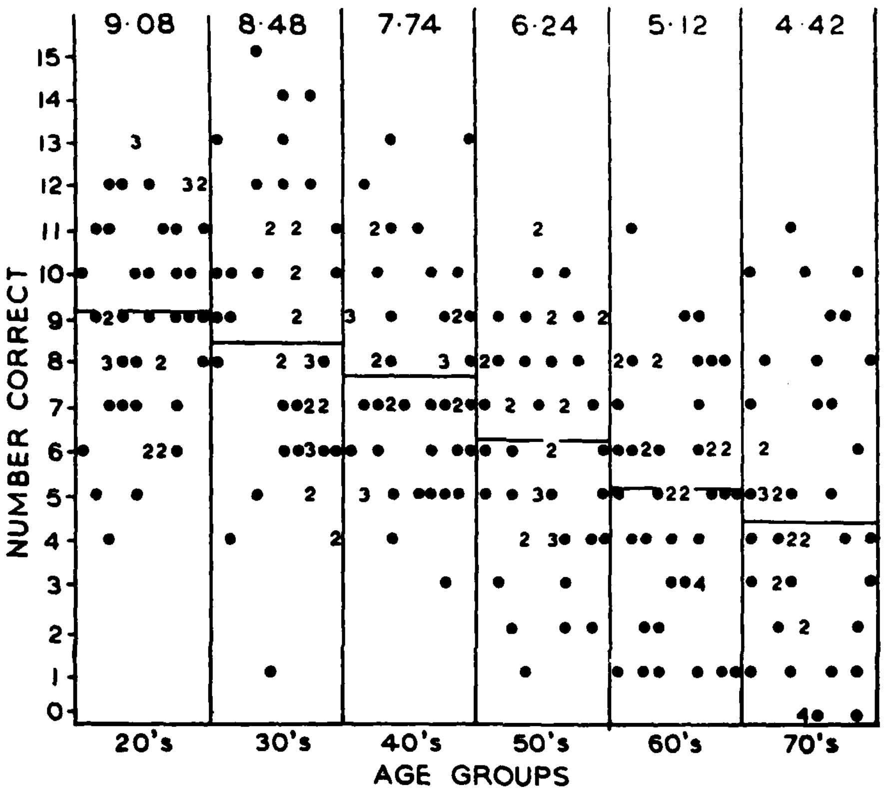


Figure 4. Number correct on Elithorn Maze Test. Distribution of scores at various ages. (Heron and Chown, 1968).

Thurstone's test of five primary abilities (1948 version) was administered to adults of different ages (a cross-sectional sample). These individuals were then repeatedly retested over time (longitudinal sampling). Every new testing, a new cross-sectional sample was taken, and the new sample was also followed longitudinally, beginning with the time of first testing. Thus Schaie and his colleagues produced parallel longitudinal samples in different cohorts.

Some of the results from Schaie's study are shown in Figure 5. As in the classic pattern, verbal performance (here identified by a vocabulary test) declined only late in life. The major discrepancy from the classic pattern may be seen in the data for spatial orientation and inductive reasoning. Schaie's measures of these abilities showed little age-specific decline until age 50. Taken at face value, Schaie's data suggest that cross-sectional findings of age differences from 20-50 are largely due to cohort effects. What might have produced these cohort effects has not been determined.

Schaie's results have generated a great deal of controversy. The issues are exemplified in an exchange between Horn and Donaldson (1976) and Baltes and Schaie (1976). The controversy is over the source of the cross-sectional age differences, and whether Schaie's data show small, but reliable, declines during middle age. From an industrial viewpoint, the resolution of the theoretical debate may not be too important. The practical question remains. If we wish to predict changes of cognitive capacity in a particular work force for a particular time period, both age and cohort effects must be known. More particularly, consider the problem of predicting the future cognitive capacities of senior personnel, drawn from today's cohort of military recruits. To do this we need to know any cohort effects over the period of interest, the cohort-specific distribution of initial (time of recruitment) test scores, and the extent to which age effects interact with initial ability.

There is, however, an important qualification to the Schaie et al. results. The generality of the age trends is restricted to the particular tests used -- Thurstone's 1948 PMA. These tests have, in the terms of psychometric test theory, high speed components and (relatively) low power components. In other words, the test items are not particularly difficult (especially for the Verbal and Number subtests). Individual differences are determined more by how fast one solves the problems rather than how difficult a problem one is capable of solving. The tests were designed to measure, at least in part, how quickly one can think about particular kinds of problems -- so the high speed components do not "invalidate" the results. They do, however, limit the inferences one can draw about the tests. The limitations could cut both ways. On the one hand, it is possible that more dfficult tests measuring spatial visualization (such as the ETS Paper Folding test) or inductive reasoning would show larger and earlier age declines than Schaie found, even if the same study design were used. On the other hand, the fact that age tends to produce a slowing in the speed of cognitive operations (see below) might suggest that the declines in PMA performance Schaie does find from age 50 to 60 indicate slowing of certain cognitive operations rather than a loss in the ability to visualize an object rotation, reason inductively,,, etc. Sequential data on tests other than Thurstone's PMA would be needed to address these questions.

THE FLUID-CRYSTALLIZED MODEL OF INTELLIGENCE AND AGING

The classic aging pattern is stated in terms of age effects on verbal and non-verbal intelligence. An alternative conceptualization has been proposed by Cattell (1971) and Horn (1978; Horn and Donaldson, 1979). They distinguish between cognitive competence based upon the application of prior learning to the present situation, and cognitive competence based upon the development of new problem solving methods devised to meet current, and perhaps novel, demands. These abilities are called crystallized and fluid intelligence, respectively. In Cattell and Horn's terms, most verbal tasks test crystallized intelligence. The capacities these tasks require, such as defining words or analyzing sentences, are based upon well practiced, culturally defined problem solving routines. Fluid intelligence is more likely to be tested by the relatively novel requirements of many nonverbal tests, such as the Raven's Matrix, in which an attempt is usually made to avoid presenting problems that have culturally defined solutions. The Cattell/Horn model also envisions other types of intelligence, such as the ability to think quickly (cognitive speed) and the ability to image a visual object (visualization). We shall be little concerned with the other intelligence types, however, for it is fluid and crystallized intelligence that are most important in the model, and which figure most prominently in the model's representation of age effects upon intelligence.

Horn and Cattell argue that crystallized intelligence increases over the adult years, as people gain a better grasp of cultural knowledge. They also argue that fluid intelligence, being a more fundamental, "biologically-based" ability to perceive relations in new information, declines from early adulthood. Figure 6 illustrates the different age trends for the two types of ability. The data are taken from a cross-sectional study by Horn and Cattell (1967). Scores for fluid and crystallized intelligence were calculated by summing scores from primary ability tests thought to relate to either fluid or crystallized intelligence. Not surprisingly, Figure 6 shows that the cross-sectional pattern for fluid and crystallized scores closely correspond to the cross-sectional pattern of the WAIS subscales.

The fluid-crystallized model of intelligence leads to the intuitively plausible notion that one should not speak of general

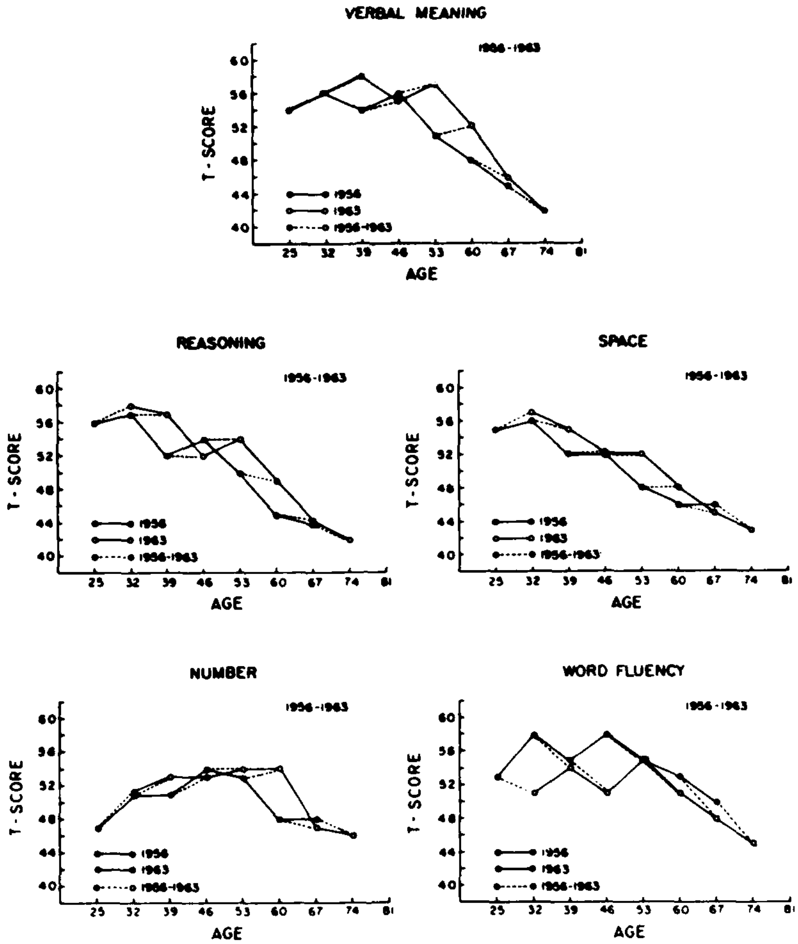


Figure 5. Changes in Primary Mental Abilities scores as a function of age, and birth cohort (Schaie, 1979).

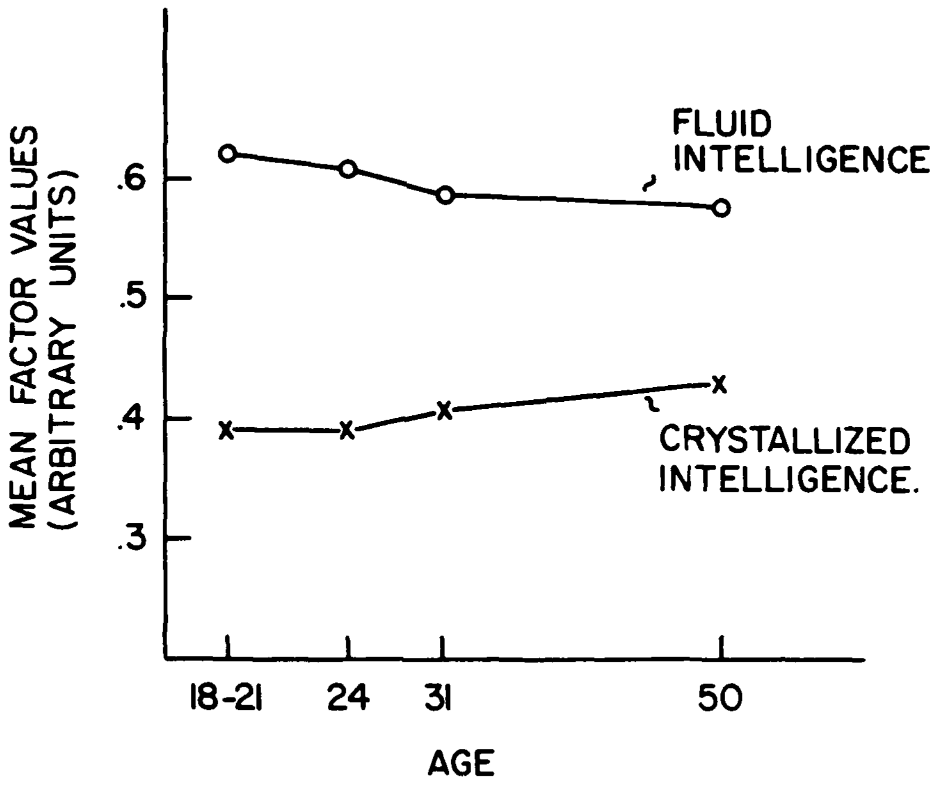


Figure 6. Mean factor scores on fluid and crystallized intelligence as a function of age. (Horn and Cattell, 1967).

decline or increase in cognitive competence. Rather, one should ask more about expression of ability in a particular situation. Is it a situation in which there are culturally defined problem solving methods that may be applied to achieve the desired result? If so, a healthy older person would be at least as adept as a young person, because the older person will probably have more knowledge about the prior utility of different solutions in similar situations. In some cases the same level of competence might be achieved in different ways. Older people would be more likely to apply relevant past experience, while younger people would be quicker at developing a new solution to the problem.

The conceptual difference between the crystallized-fluid distinction and the verbal-nonverbal distinction has important practical implications. If the crucial variable is experience, and not the extent to which a problem requires verbal skills, then one would expect to find situations in which older persons with appropriate experience would maintain skills in nonverbal situations. To illustrate by hypothetical example, consider the case of an aircraft mechanic who is assigned to recruiting duty, and then is returned to his specialty at age 40 or 45. Since tool use is a spatial skill (McGee, 1979), proponents of the verbal-nonverbal distinction would predict that there should be deterioration in the mechanic's skill. The fluid-crystallized model would predict that, if there is substantial similarity between the current task and tasks assigned prior to the interruption in the mechanic's career, then the mechanic should have little problem in applying old skills to master the new task. The practical interpretation of the debate revolves around the question of whether older personnel should be shifted toward assignments involving more verbal tasks, or maintained in familiar assignments even if they require spatial skills. If the fluid-crystallized model is correct, an effort should be made to ensure greater continuity of procedures and demands in duty assignments of older personnel. A similar argument would be made regarding the optimal training techniques for older personnel. Assuming the fluid-crystallized distinction to be true, one would argue that nonverbal training techniques would be acceptable for older personnel, providing that they utilized concepts and knowledge familiar to the trainees. Indeed, given trainees of average (or below average) verbal intelligence, it would be foolish to provide training by purely verbal methods (e.g., reading training manuals) because there was relative maintenance of verbal skills with advancing age.

The current literature is inadequate to distinguish between the verbal-nonverbal and crystallized-fluid explanations of the classic aging pattern. While one can think of tasks that should be verbal-fluid and, with somewhat more difficulty, tasks that should be nonverbal-crystallized, no systematic study of such tasks has been conducted.

Before moving to other aspects of the literature on intelligence, we enter a reservation concerning the classic aging pattern. A person taking a psychometric test is faced with a particular problem solving situation, and must develop techniques for coping with that situation "on the spot." Tests of verbal intelligence ask people to read paragraphs, retrieve the definitions of words, etc. Nonverbal tests typically present adults with rather novel problem solving situations. This is particularly true of the so called "culture-fair" tests, which explicitly seek to minimize capitalization on previous knowledge. Horn and Cattell would argue that this is precisely the source of the crystallized-fluid difference. But there is an additional confounding factor, the amount and recency of previous experience individuals have with test taking. Young adults who have recently been in school will have had a good deal of experience dealing with testing situations, and probably develop skills to cope with them. Older persons, who may have had less schooling, and almost certainly have not recently been in school, probably do not have these skills available. Is it possible, then, that the apparent decline in fluid intelligence is an artifact that could be removed by proper training? The issue is a complex one. There is little doubt that older people can improve their absolute scores with training (e.g., Willis, 1981). Improving test scores, however, is not the point, unless the improved scores also predict performance outside the test situation better than do the scores obtained prior to training.

CHANGES IN THE STRUCTURE OF INTELLIGENCE WITH AGE

The "structure of intelligence" refers to the relations between different psychometric abilities, which is in turn a function of the relations between those abilities and the more basic cognitive capacities that determine them. The correlations among performance on measures of different primary abilities are said to be determined by the underlying intellectual structure. Spearman's famous "general plus specific" theory of intelligence, the Cattell-Horn model, and Thurstone's primary mental abilities model are all models of the structure of intelligence. Although most studies of age changes in intelligence have examined age changes in mean ability levels, some studies have asked whether there are fundamental changes in the structure of abilities with advancing age.

Studies of young adults tend to find smaller correlation between different abilities than do studies using children. Young adults are more likely to be good at some skills and poor at others, while children tend to be generally good or bad. Older adults tend to show less differentiation between different abilities. This hypothesis is called de-differentiation (Reinert, 1970). One possible account for this hypothesis, if it is indeed true, is that age declines in basic cognitive operations, especially in their speed of execution, tend to reduce performance levels of older adults on all ability tests

Table 1

Correlations among Primary Mental Abilities Factors

Group 1 (Mean age 30)

	V	S	R	N	W
V	1				
S	.115	1			
R	.559	.455	1		
N	.390	.239	.489	1	
W	.531	.034	.425	.334	1

Group 2 (Mean age 42)

V	1				
S	.296	1			
R	.711	.479	1		
N	.419	.248	.441	1	
W	.508	.039	.439	.308	1

Group 3 (Mean age 58)

V	1				
S	.593	1			
R	.838	.650	1		
N	.666	.528	.627	1	
W	.557	.290	.505	.450	1

Data from Hertzog, 1979. Only the lower half of the (symmetric) correlation matrix is shown. Mean age refers to age at first testing in longitudinal sequence.

Abbreviations:
V - Verbal
S - Spatial Rotations
R - Reasoning (Inductive)
N - Number
W - Word Fluency

(Cunningham and Birren, 1981). Taken to the extreme, the dedifferentiation hypothesis imples that tests of ability that are valid for young adults are invalid for older adults because the tests are not measuring the same cognitive abilities in the two populations. This is an important issue for any method of occupational screening of older adults which is based upon conventional psychometric tests.

Earlier studies of the dedifferentiation hypothesis used factor analytic methods to isolate sources of association among different intelligence tests. This is a statistical technique that is supposed to uncover the underlying dimensions of abilities that are tested, in different ways, by each of a large battery of tests. The dedifferentiation hypothesis predicts that several dimensions will be uncovered by analyzing the data from tests given to young adults, and that fewer (perhaps only one) dimension will be found in the data obtained from older adults. The results of early studies testing the dedifferentiation hypothesis were inconsistent (Reinert, 1970) Much of the disagreement seems to have been due to differences in factor analytic methods used from study to study, rather than in inconsistencies in the data itself. Recent studies have used more advanced methods to compare factor analytic solutions obtained from different age groups. A more consistent picture has emerged. There does appear to be an increase in the correlations among ability factors in late middle age and old age (Cunningham, 1980; Cunningham and Birren, 1981; Hertzog, 1979). Table 1 reports correlations among five primary ability factors for three different age groups from the Hertzog study. The correlations among abilities in the oldest group were uniformly higher than the same correlations in the youngest group. Note, however, that most of the changes appear to emerge from middle to old age.

In spite of the changing correlations among ability factors, the recent results indicate that the relationship between individual psychometric tests and the underlying ability factors seems to be constant into old age. This conclusion is based upon the observation that the regressions of tests on factors (the factor loadings) from these factor analyses may be considered equivalent for different age groups (Cunningham, 1980; Hertzog, 1979). We may interpret the changing correlations as an indication of a modest form of dedifferentiation, which is of theoretical interest. Why would conceptually distinct abilities become more correlated with advancing age? However, the major changes occur after age 50 and, more importantly, do not appear to affect the basic measurement properties of the psychometric tests. The data therefore causes little concern that age changes in intellectual structure invalidate the use of psychometric tests for occupational purposes for adults under the age of 55.

The Hertzog analysis, based upon Schaie's longitudinal data, adds another bit of useful information about the stability of mental performance. The study found that absolute variability in a general intelligence factor increased from roughly age 40, and that individual differences in intelligence were highly stable across the adult life span. The latter point was indicated by correlations exceeding .9 between general intelligence measured longitudinally over a 14 year age interval. This correlation is even higher than the .7 correlation typically found between adolescent and adult performance (McCall, 1977). Hertzog's results show that, in spite of any age changes in level of performance, the relative ordering of adults on a general intelligence factor remains basically constant over time. They further show that average differences between individuals in this general intelligence factor increase as they grow older. This finding is of considerable practical importance for selection of personnel. Given that two individuals differ slightly in intelligence at age 20, the prognosis is that the difference may be greater, but will be in the same direction, at age 50. When considered in conjunction with the evidence that high ability individuals may maintain higher mean levels of performance (that is, show less age decline) than lower ability individuals, these results provide a scientific rationale for increased efforts to recruit higher ability level personnel initially, and to try to keep them in the service longer. The intelligent recruits today will probably be intelligent (and experienced) personnel later. There is a minor qualification to this interpretation of the Hertzog results. One must remember that the high correlations between different ages found in that study are for an intelligence factor defined by the covariances among several intelligence tests. Measurement error (see Nunnally, 1978) will limit the between-ages correlation (and hence, the predictive validity) of any single intelligence test.

We argued above that the psychometric data provide useful global information about age changes in cognition, while the experimental data on age changes in cognitive processes provides, in principle, a more refined picture of aging effects on cognitive activity. One could also argue that a joint analysis of intelligence and information processing capacity is needed to explain more fully the age effects on psychometric intelligence that are observed -- intelligence may be best understood when considered in light of information processing models (Hunt, 1978,1980). Horn and Donaldson (1979) also contend that complex skills such as those tested in psychometric studies must be based partly upon acquired knowledge, and partly upon more primitive information processing capacities. In some of his studies, Horn has attempted to measure these more primitive capacities, and relate age differences in information processing capacity to age differences in fluid and crystallized intelligence. His data suggest that the information processing measures are more closely related to fluid intelligence, as predicted. Figure 7 summarizes the results of statistical manipulations in which the conditional distribution of fluid intelligence are related to age, after age differences in measures of attention and short term memory are held constant by part correlation. The dashed lines are the

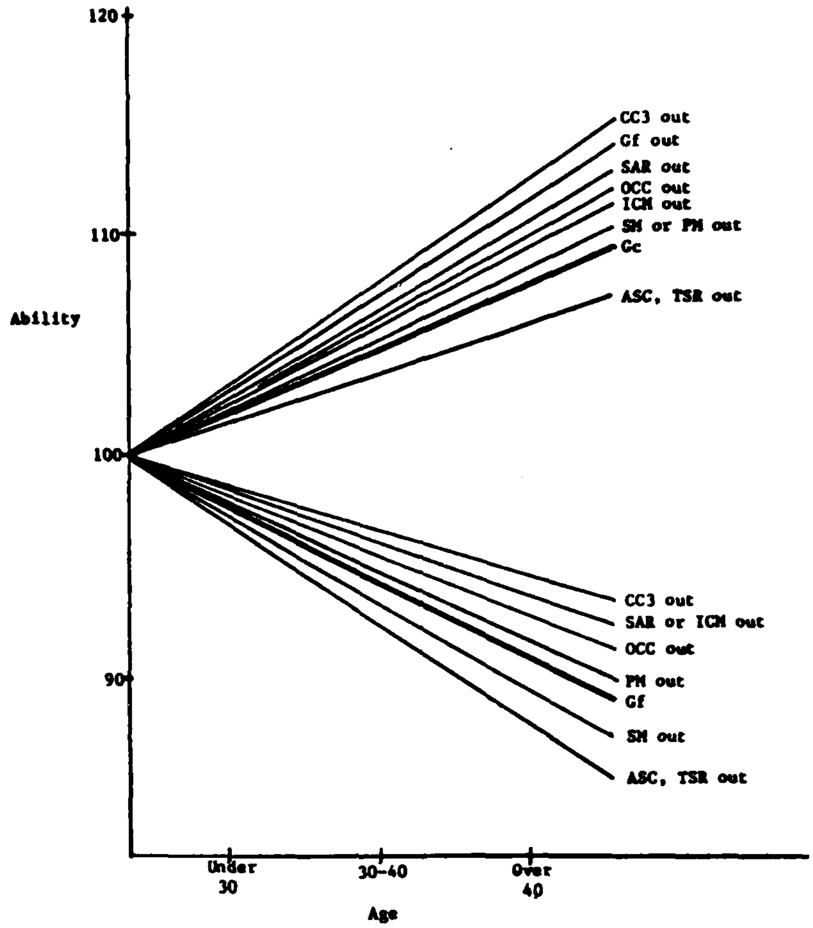


Figure 7. Idealized plot of changes in ability. (Horn and Donaldson, 1979). Note the lines labeled "Gf" and "Gc". These refer to factor loadings on fluid and crystallized abilities respectively. The upper fan shows change in crystallized ability obtained by holding various other age-sensitive abilities constant. For example, line SAR refers to changes in crystallized ability after allowing for age changes in a short term memory factor. The lower fan shows a similar plot for the fluid intelligence factor.

adjusted age trends, while the solid lines are the unadjusted trends. There is a significant reduction in the age trend for fluid intelligence after adjustment for the information processing measures. While we have reservations about the measures Horn used, and the use of part correlation, the general hypothesis that age trends in intelligence performance are related to age trends in information processing skills merits further investigation.

SUMMARY

The literature on age changes in psychometric intelligence suggests that there are changes during the working years in mean performance levels on at least some abilities. Spatial ability and non verbal reasoning tests ("fluid intelligence") seem to be particularly susceptible. Whether or not the drop in non-verbal reasoning and spatial performance occurs before or after age 50 is a matter of debate. Although there are several cross-sectional studies that suggest that the drop begins reasonably early in adult life (roughly 30 to 35), these studies have not adequately controlled for cohort effects. The reports from the better controlled experiments by Schaie et al., in which cohort effects were measured, suggests that the drop begins place sometime past 50. Because of the industrial importance of this question, a replication of Schaie's work, using other populations, would be highly desirable in spite of its expense.

Virtually all psychometric studies have concluded that there is considerable stability in levels of verbal intelligence during the working years.

4. SENSORY CAPACITIES

In some situations people function simply as detection and recognition devices. The complexity of a detection and recognition task can vary greatly from detection of a signal's presence to identification of a particular signal in the presence of distractors. Performance in primitive detection functions is generally limited by end organ sensitivity, while performance in more complex tasks is limited by central nervous system (CNS) functioning. Both the sensory end-organs and the CNS systems involved in sensory information analysis appear to be sensitive to aging. In some cases marked environmental effects are also observed, that may appear to be age effects as people live in the hazardous environments. As a general rule, sensory functioning in all modalities declines over the working years. The details of the various changes have been documented for vision (Fozard, Wolf, Bell, McFarland, and Podolsky, 1977; Weale, 1963, 1965), audition

(Bergman, 1980; Corso, 1977; Ordy, Brizzee, Beavers, and Medart, 1979), and olfaction (Engen, 1977). We will cover vision and audition only, as they are by far the most important modalities in man.

VISION-DETECTION AND PERIPHERAL EFFECTS

Perhaps the best summary statement about vision is that it changes considerably over the working years, but that in the normal adult it remains our most reliable sensory system.

The eye itself undergoes detectable changes relatively early in adult life. By age 40 the cornea shows a loss of lustre that is probably associated with a change in corneal refractive power. There is also an increase in the incidence of corneal "arcus senilis", a grey ring on the outer band of the cornea due to lipid accumulation. This condition occurs in less than 1% of the population before age 20, but it occurs in about 50% of the population by age 50. Less obvious physical changes are also found. Past 50 the curvature and thickness of the cornea increases, making acuity-independent astigmatisms more likely. The pupil decreases in size from adolescence, and the latency of the pupillary reflex increases with age. By 40 the lens mass, volume, and density has increased, producing reduced accomodation. This change is linear with age. The lens yellows in color, producing a filtering effect on incident light. The largest effects are in the blue-green region of the spectrum. The lens changes its refraction index, causing a blurring of the retinal image. Given these phenomena of normal aging, it is hardly surprising that middle-aged tennis players complain about outdoor night lighting! On a more serious note, it is clear that physical changes in the eye do produce observable, although tolerable, visual problems by the 40s.

In addition to the normal processes of organ deterioration, the risk of pathological change increases with age. Glaucoma, cataracts, and most seriously, retinal deterioration due to untreated diabetes, are serious problems beyond 45.

The net effect of these end organ changes is to produce easily measurable changes in sensitivity and in light-dark adaptation in the middle aged. Obviously people in their 40s are not blind, but their eyesight is deteriorating in an industrially significant manner. The problem can be acute if the work situation requires the detection of weak signals in low levels of illumination, even after time has been allowed for dark adaptation. Figure 8 summarizes data reported by McFarland, Domey, Warren, and Ward (1960) on visual sensitivity during the process of dark adaptation. The figure shows clearly that both the rate of adaptation and the asymptotic sensitivity after adaptation decrease from youth to middle age. This is something

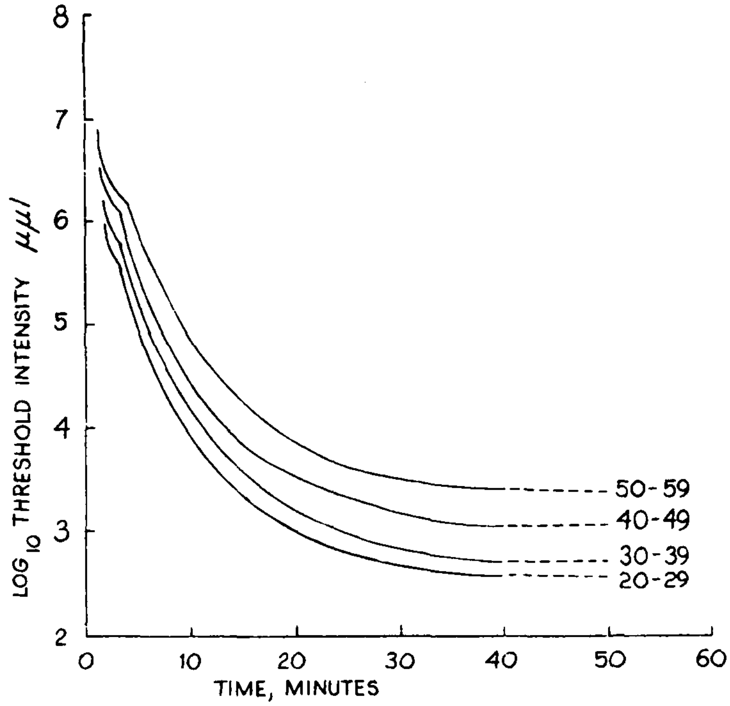


Figure 8. Threshold for defection of light as a function of age and time in dark. (McFarland et. al., 1960).

one should be aware of in setting standards for performance in any situation that requires movement from lighted to darkened areas.

The glare produced by high illumination also becomes increasingly troublesome after age 40, due to increased yellowing of the lens (Reading, 1968; Wolf and Gardiner, 1965). The filtering of the aging lens differs according to the light's wavelength. Adaptation to glare from white light is faster than adaptation to yellow light in young adults, but the difference between adaptation to white or yellow light is reduced for older individuals (Reading, 1968). Thus older personnel should be more able than younger personnel to benefit from a human's relatively high sensitivity to yellow light while being less affected by glare. Whether this effect would be large enough to justify use of yellow lights in some environments is a question that should be studied further.

Industrial situations in which people are asked to detect visual signals in fixed fields are probably rather rare. A more common situation is one in which a person must alternate between gazing at relatively close displays and searching a distant visual field. This occurs, for instance, when a person must alternate between looking out of a vehicle and glancing at the control panel. In order to do this, the eye must accomodate rapidly to vision at different distances. Formally, accomodation is defined as the ability of the eye to focus sharp retinal images of external objects independent of object distance (Weale, 1963). The data shows that accomodation from far vision to near vision deteriorates with age (Bruckner,1967). This change is often referred to as "presbyopia." The sharpest declines occur shortly after age 40 -- there is a mean accomodation change of from 5 to 2 diopters from age 40 to age 55. This change indicates that the average 40 year old can change focus from the far point to a near point of about 6 cm., but the average 55 year old can only shift focus to a near point of about 50 cm. Objects closer than 50 cm can no longer be maintained in sharp focus. There is also evidence that the ability of the eye to accomodate can be affected by the environment, for instance by long term duty on submarines (Kinney et al, Note 3). The possibility that age changes in vision can be exacerbated by particular environments should be given more study.

Presbyotic changes in the visual near point appear to be caused by changes in the shape of the eye, senile degeneration of the ciliary body and ocular muscles, and loss of flexibility in the lens. As is well known, these changes also can result in refractive changes which cause a deterioration of visual acuity at the near point. Put simply, the magnitude of the optical correction required for reading increases exponentially as a function of age (Weale, 1963). By age 50 a significant proportion of the population requires glasses with a reading correction (Bernstein and Bernstein, 1945). Visual acuity for far vision also shows a decided drop with age. Figure 9 shows age stratified data on visual acuity at the far point (20 foot distance) compiled by the National Center for Health Statistics (Department of Health, Education, and Welfare, 1977). There is a sharp decline after ages 40-45 in the percentage of individuals having 20/20 vision, and a corresponding increase in the percentage of individuals with 20/50 vision or worse. Experimental tests of visual acuity also show age declines during middle age (e.g., Eriksen, Hamlin, and Breitmeyer, 1970).

The preceding data showed age changes in static visual acuity, or accuracy in perceiving the features of a stationary object. Dynamic visual acuity is defined as accuracy in perceiving features of a moving object. Dynamic visual acuity also declines with age. Burg (1966) and Heron and Chown (1967) tested dynamic acuity by having observers discriminate features of an object rotating in a fixed position in the visual field. Burg's data (Figure 10A) tend to show earlier and larger age declines in dynamic acuity than Heron and Chown's (Figure 10B). The difference may be due to the range of visual acuity tested. Burg's targets subtended smaller visual angles than did Heron and Chown's. Regardless of the details, the existence of an age-related change in dynamic acuity for a rotating object is clear.

Reading (1972) had observers (20-30 years; 40-50 years) track a target moving with varying angular velocity across the visual field. The task was to detect the presence or absence of a small gap in an oval. The data, shown in Figure 11, follow the function

$$Y = M + NX^3 \qquad (1)$$

where Y is resolution acuity, X is the angular velocity (in degrees/sec.), M is an intercept parameter (corresponding to static acuity at X = 0), and N is a dynamic acuity parameter. Reading found that separate M and N parameters were required for the two age groups. The static acuity parameter was 113% greater for the 40-50 year olds, while the dynamic acuity parameter was about 50% greater. The two parameters were virtually uncorrelated. Thus, independent age changes in both static and dynamic acuity were found from age 20 to age 50.

Another age change in vision that may have military implications is the shrinkage of the functional visual field (Burg, 1966; Wolf, 1967). Wolf's data suggest that the shrinkage rate is greatest after age 50, although small changes do occur earlier in life. It is well known that the orienting response to a moving object beyond the point of focal attention involves mechanisms associated with motion detection in the periphery. Whether the restrictions in the functional size of the peripheral visual field would impair an older persons's ability to detect such objects (particularly in conjunction with reduced dynamic acuity) is an important, yet unanswered, question.

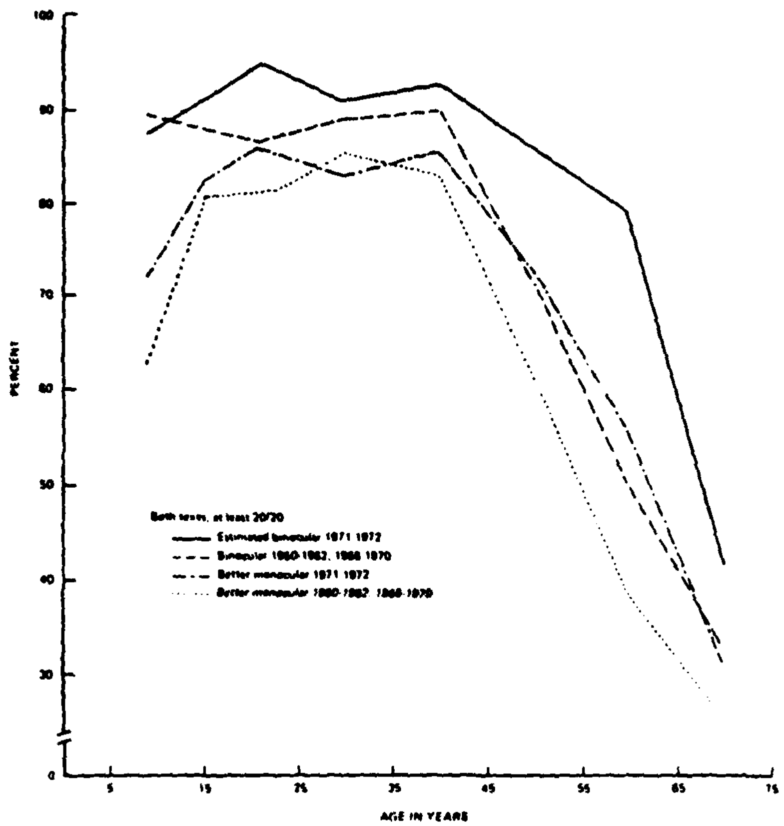


Figure 9. Percentage of population with 20/20 vision as a function of age. Various estimates are shown.

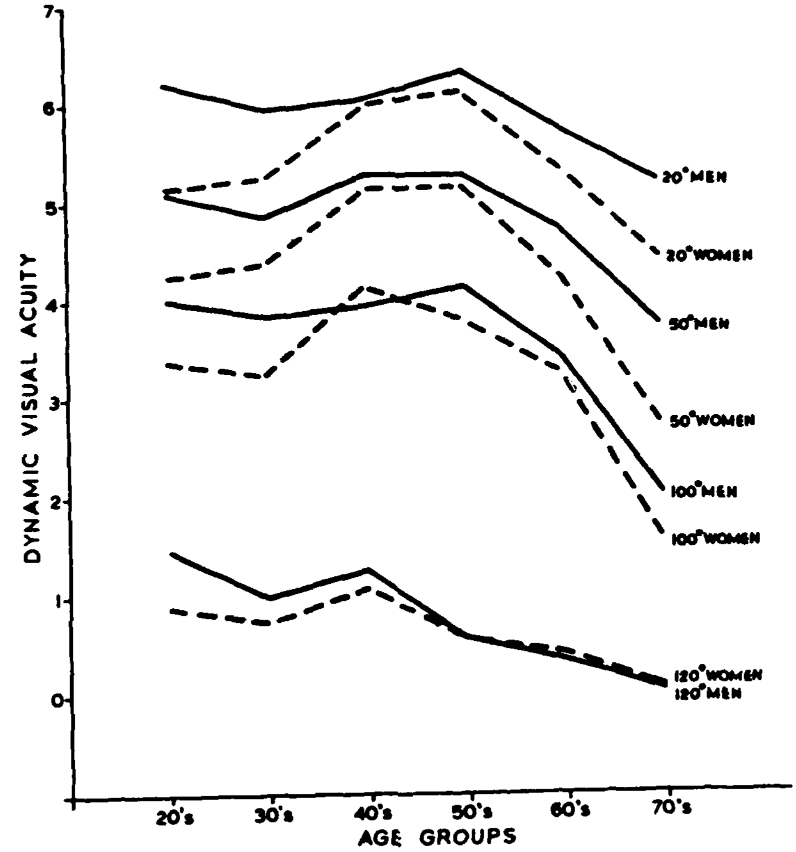


Figure 10a. Dynamic visual acuity: Minimum gap in ring detected with target moving at the angular velocity indicated by the curve parameter. Data from Burg (1966).

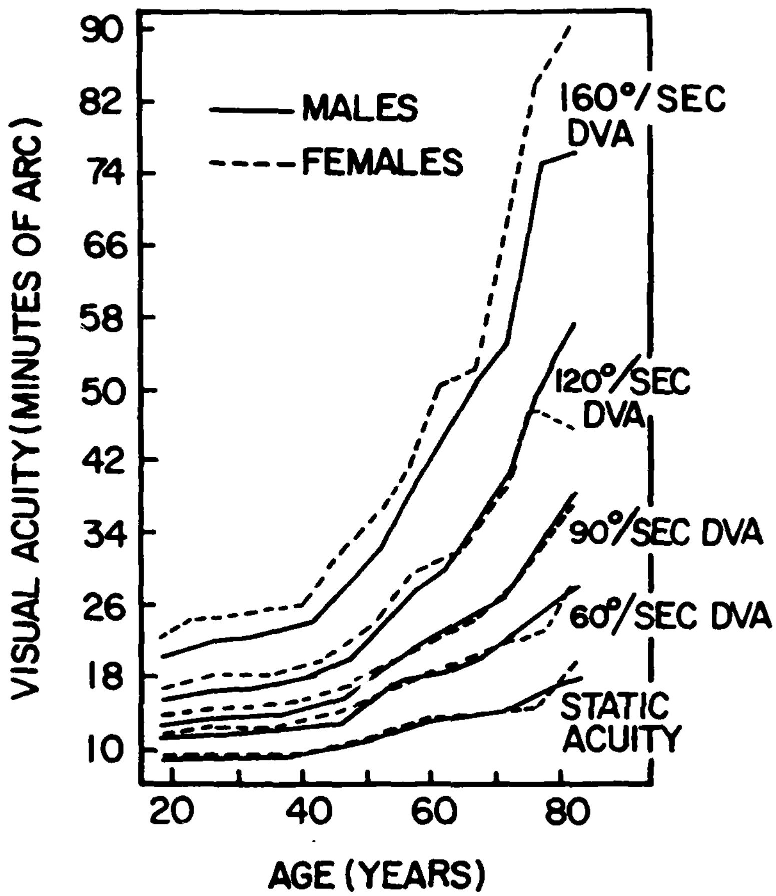


Figure 10b. Dynamic visual acuity: Minimum gap in ring detected with target moving at the angular velocity indicated by the curve parameter. Data from Heron and Chown (1967).

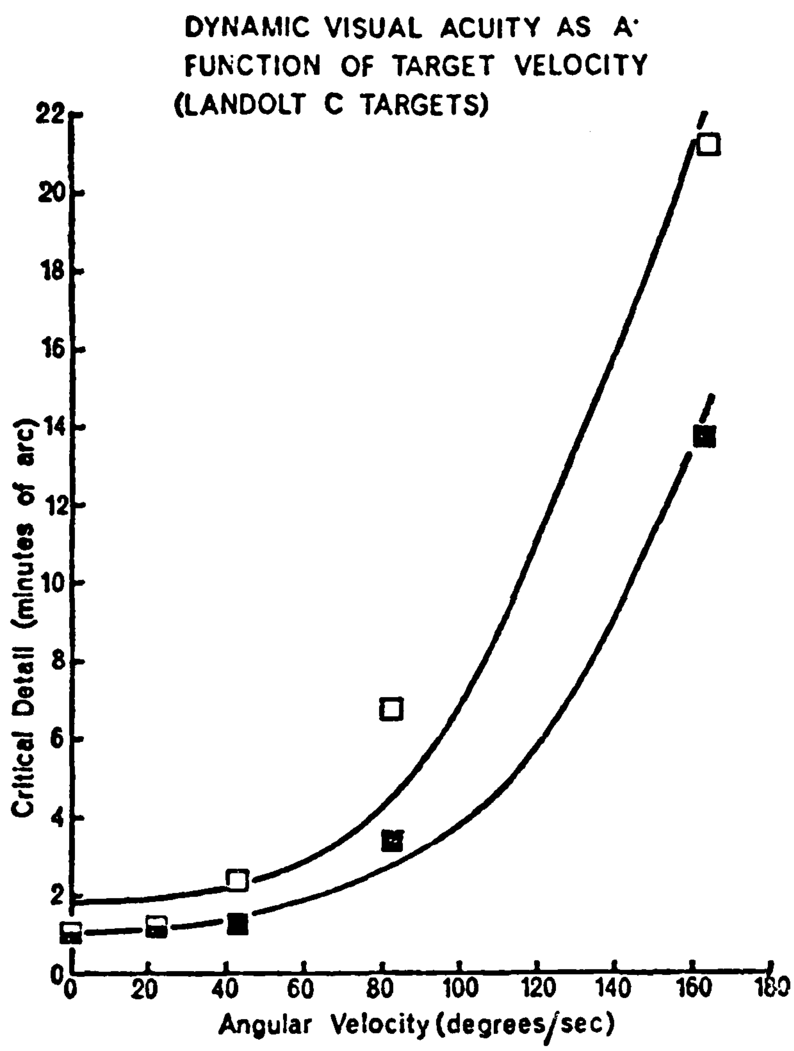


Figure 11. Dynamic visual acuity as a function of target velocity and age (open squares, observers 40-50, closed squares, observers 20-30).
Data from Reading, 1972.

Not all aspects of vision show large declines during or before middle age. Depth perception appears to be stable until at least age 40 to 45. The age changes in depth perception that have been reported appear to have been confounded with age changes in accomodation and convergence, and are not age changes in depth perception per se (Bell, Wolf, and Bernholz, 1972).

To summarize, age-related changes in the eye result in changes in many visual functions, including dark adaptation, accomodation, static and dynamic acuity, and functional size of the visual field. While these changes are not large enough to warrant a general rule that middle aged personnel cannot or should not do particular tasks, they are large enough to warrant extended testing of visual capacity beyond the middle thirties. This is particularly true if a person might be assigned to duty requiring a high level of vision. We emphasize that standard test of static acuity, such as the familiar eye chart, would probably not be adequate as a predictor of performance for middle aged personnel. This point is underscored by results reported by Sivak, Olson, and Pastalan (1981). They examined age changes in night vision for reading traffic signs in a field situation. Two groups of individuals (mean ages 33 and 66) were required to discriminate a small retroflect sign while driving or riding in a car. The groups were matched for static acuity at high brightness levels. Sivak et al. found the greatest distance at which the sign could be read by the young and old drivers. The greatest distance for the older drivers was only 65 - 77% that of the younger drivers. In terms of functioning, if older and younger drivers were traveling along a road at the same speed, the older drivers would have less time to react to a warning sign. Perhaps the most important point of the Sivak et al. study is that the functional disparity in vision shown between old and young in the driving situation was not predicted by their equivalent performance in a high brightness test of static acuity. This is consistent with data on driving behavior in field situations. Hills (1980), in reviewing the literature on perception and driving, notes that the breakpoint for age-related increases in accident rates coincides with the age of increasing decline in dynamic visual acuity. The correlation between dynamic visual acuity and driving accidents is largest in older populations, while the relation to static acuity remains low (Hills, 1980; Henderson and Burg, Note 4).

CENTRAL CHANGES IN VISUAL INFORMATION PROCESSING

The visual nervous system is organized into a highly complex network of visual "channels," hierarchically ordered networks of brain cells designed to be sensitive to specific visual features in precise spatial locations in the visual field. Visual channels are selectively activated according to the salient properties of the visual stimulus, especially size, orientation, contrast ratio, and spatial frequency. Recent evidence collected by Sekuler, Hutman, and Owsley (1980) suggests greater age decline in the sensitivity of channels tuned to low spatial frequency information. Sekuler et al. examined the ability of old and young subjects to discriminate vertical gratings varying in spatial frequency (frequencies ranging from .5 to 16 cycles/degree). There were no age differences at high spatial frequencies, but age differences in contrast sensitivity emerged, and increased progressively, as spatial frequency decreased. These changes were not a function of ocular pathology or poor visual acuity. More work is needed to determine the age at which this change in low spatial frequency sensitivity occurs, and to determine which levels of the visual nervous system contribute to the effect.

Other reports have indicated age declines in the quality of visual information processing. Szafran (1968) examined recognition thresholds for shapes, numbers, letters, and words, using young and old commercial pilots as observers. He calculated channel capacity curves by plotting output information (in bits) against input information. There were small, but reliable age changes in the information transmitted, although individual differences were large relative to the size of the age effects. These and other results led Szafran (1968) to suggest that age changes in visual information analysis are a function of age increases in the level of internal "neural noise" in the visual system. Gregory (1957; see also Vickers, Nettlebeck, and Wilson, 1972) advanced a similar hypothesis, based upon some evidence of age changes in differential thresholds. Although widely cited (e.g., Welford, 1981), the neural noise hypothesis has yet to receive a definitive test. Indeed, we regard the data of Szafran (1968) and Gregory (1957) for age changes in the accuracy of visual discrimination as preliminary.

There is good evidence for age changes in the speed of information processing by the visual channels. Most studies of the speed of identification of visual stimuli use some variant of an experimental paradigm known as visual masking. The events in a masking study are shown in Figure 12. First a target stimulus is presented, at an intensity that would ensure easy detection were it to be left in front of the observer indefinitely. The target stimulus is followed by a masking stimulus (or "mask") which overrides the visual image of the initial stimulus. The time between initiation of the stimulus and the mask is called the Stimulus Onset Asynchrony (SOA). The SOA can be thought of as the sum of two parts: the time the target is displayed, or the target duration (TD), and the dead time inbetween the target and mask, the interstimulus interval (ISI). The purpose of a masking experiment is to determine the shortest SOA (sometimes, the shortest ISI) at which an observer can make a reliable identification of the target stimulus. This shortest SOA is called the masking threshold. It may be used as a measure of the speed of visual identification.

Turvey (Turvey, 1973; Michaels and Turvey, 1979) has shown

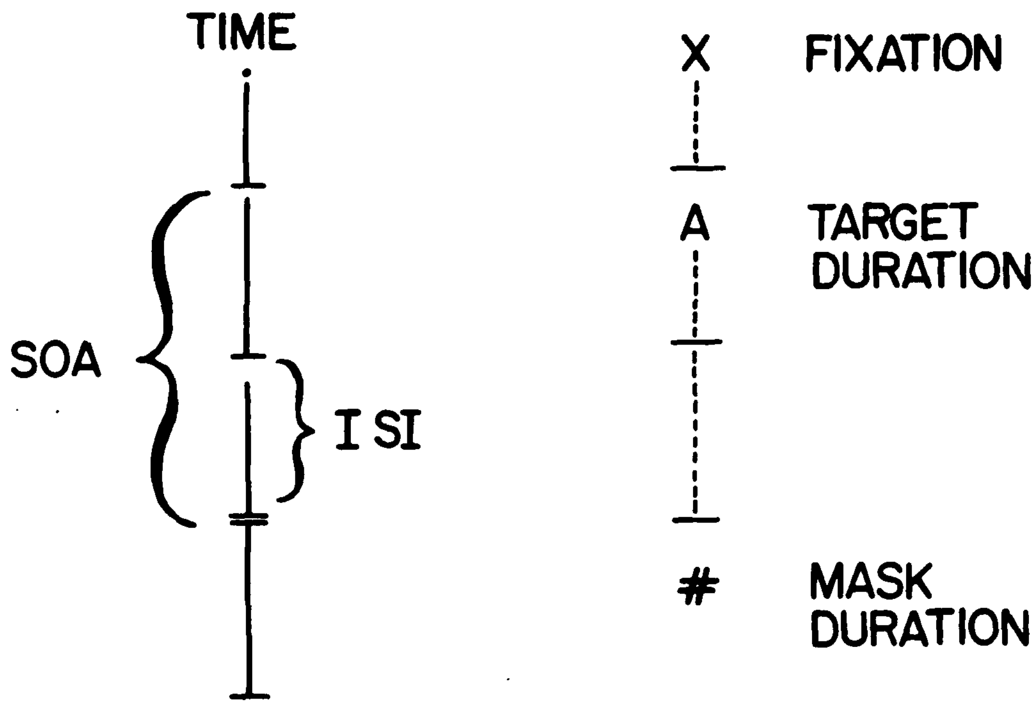


Figure 12. Sequence of events in visual masking.

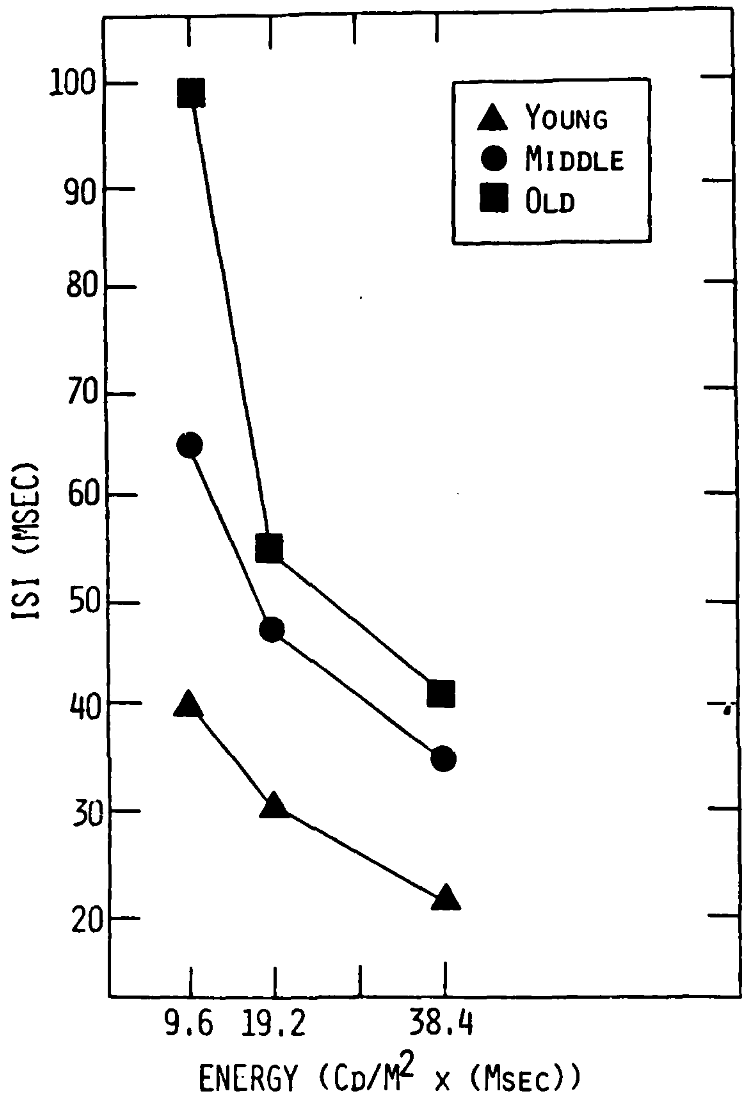


Figure 13. Interstimulus interval to escape peripheral masking, as a function of age and intensity of target. (After Walsh, Note 5).

that there are at least two different types of masking. Peripheral masking effects, which are largely controlled by the physical intensity of the mask, arise primarily because the target and mask stimuli are integrated into a single functional stimulus in the earliest stages of visual processing. Central masking phenomena depend upon the perceptual relation between the stimulus and the mask. Central masking is greatest if the mask is constructed of visual features similar to those used to construct the stimulus. These are called "pattern masks." The central nature of masking is shown by the fact that pattern masks are effective under dichoptic presentations -- i.e., when the mask is presented to one eye and the target to the other.

As its name implies, peripheral masking is thought to be due to the interaction between the target and mask in the peripheral visual system (the retinal and visual tract prior to the point of the fusing of information from the two eyes). Peripheral masking depends upon the intensity of illumination of the target and mask, in accordance with the following rule:

$$(2) \qquad TE^{B} \times SOA = K ,$$

where TE is the target energy, B is an unknown exponent, SOA is the critical SOA, and K is a constant. K is characteristic of an individual's performance at a set level of accuracy. What the rule in Equation 2 indicates is that the masking threshold (SOA) decreases as target energy increases. In fact, above a certain level of target energy, which varies from person to person, no masking occurs.

Age differences between young and old adults have been found in peripheral masking, and appear to be restricted mostly to K and not B (Till, 1978; Walsh, Till, and Williams, 1978). In other words, age does not seem to change the form of the power function, but older persons require longer SOAs to escape the masking function. Walsh (Note 4) recently reported peripheral masking data which included a middle age group. His sample consisted of 24 young (mean age 18.7 years, range 17-21 years), 24 middle aged (mean age 46.5, range 40-53), and 24 old (mean age 70.3, range 7-74 years) adults, who were either University students or alumni. The critical ISI to escape masking is shown in Figure 13. There appear to be reliable differences in the peripheral masking constant between the young and middle aged subjects (the exponent B did not differ between them). This result means that, for a fixed target energy, the middle aged persons were susceptible to masking for a longer time. Note that the data for the middle aged observers were more like the data for the older observers.

The age increase in peripheral masking thresholds could be attributed to two sources: decreased energy incident at the retina (because of yellowing of the lens and other effects discussed above), or slowed transmission time in the peripheral visual channels. Walsh (Note 5; Walsh, Till, and Williams, 1978) argues that the effect probably represents slowed peripheral channel analysis, since individual differences in thresholds for the target stimuli alone account for relatively small amount of the variance in ISI across individuals in each age group. The evidence for the exclusion of ocular factors is still scanty, however, and further research on this question would be in order.

Unlike peripheral masking, central masking is relatively independent of target and mask energies. Instead it appears to be a function of the time needed to decode the visual features of the target and then identify it. Central masking obeys the rule:

$$(3) \qquad SOA = TD + ISI = K ,$$

where SOA is the critical SOA to escape masking, TD is the target duration, ISI is the critical ISI to escape masking, and K is a central masking constant. The K in Equation 3 is also a characteristic of a given individual and level of accuracy, but it is different from the constant of the peripheral rule (Equation 2).

Age differences in central masking have been shown by age 50 (Walsh, Note 5; Williams, Note 6). Walsh found SOAs of approximately 50, 60, and 65 msec for his 20, 46, and 70 year old groups, respectively (these SOAs are inexplicably shorter than those of previous studies in the same laboratory -- e.g., Walsh, Williams, and Hertzog, 1979). In Walsh's studies, the target stimuli are letters. Walsh (Note 5) also varied the number of letters in the target from 1 to 3. Masking thresholds for multiple element targets are of interest because the additional time taken to identify the extra targets reflects readout time of information from a short term visual storage system often called "iconic memory". Walsh' data are shown in Figure 14. He assumed that the letters were read out of iconic memory one at a time, and therefore fit a linear equation to the data (the thin lines in Figure 14). Even without committing oneself to the validity of the serial readout assumption (Sperling, 67), The slope of the linear equation may be taken as a rough measure of the speed of information readout from iconic memory. As can be seen from Figure 14, the increase in SOA from 1 to 3 letter targets appears to interact with age -- note the roughly 40 msec. difference between young and middle aged individuals for the 3 letter targets. These results suggest slowed iconic readout by age 45. It would be desireable to extend the research to find the age where the decline in iconic readout speed begins.

In absolute terms, age differences in masking thresholds are not large. The difference between observers in their 20s and 60s in SOAs for single letter targets is on the order of 25 msec. This difference is small relative to age differences in motor reaction times (see below). Nevertheless, any age effects on masking functions are of interest because of their theoretical interpretation. Central masking, in particular, provides a fairly direct measure of the speed of information processing in the

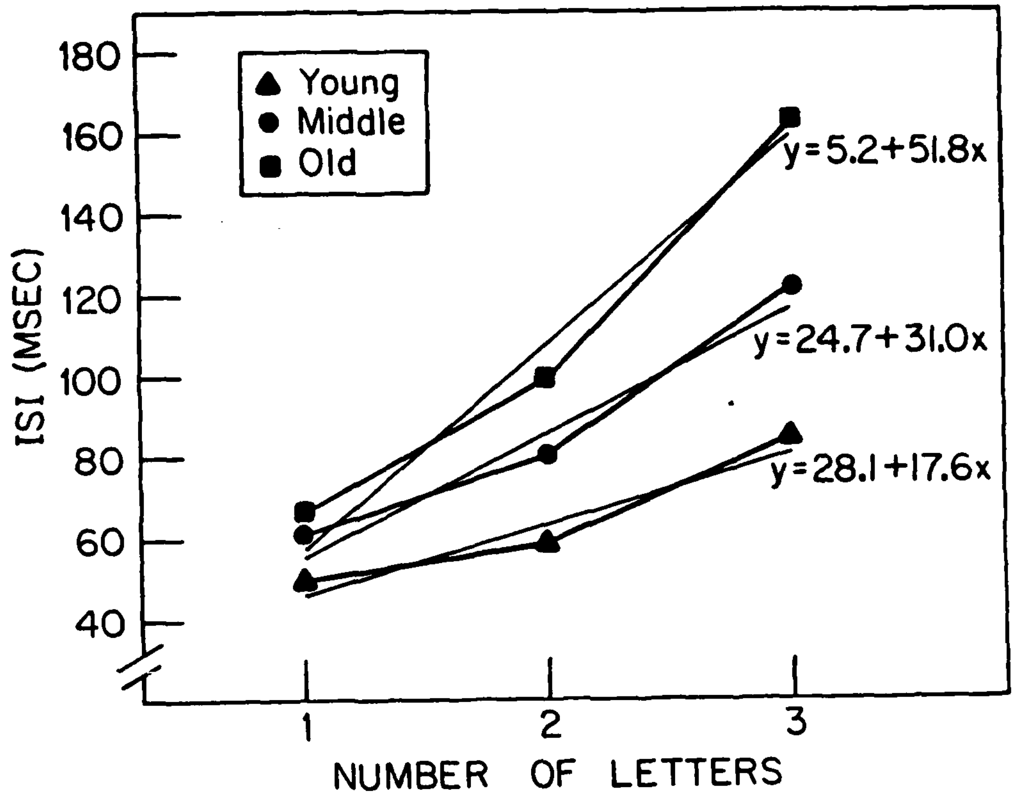


Figure 14. Interstimulus interval required for correct recall of letters in central masking paradigm, as a function of age and number of letters. (Walsh, et. al., 1979).

A R Q S T

V X T L A

F Y R S B

VISUAL SCANNING: THE TASK
IS TO LOCATE LINES CONTAINING
AN "X"

Figure 15. Visual scanning task.

visual nervous system. Changes in masking do appear to occur by middle age. Furthermore, studies measuring the brains electrical response during stimulus identification also show slowing of brain activity with advancing age (Ford and Pfefferbaum, 1980). Thus a modest decline in masking may be an indication of a pervasive slowing process that could have multiplicative effects in complex problem solving situations. As we shall see, there is a good deal of evidence to show that a generalized slowing of cognitive processes does occur with age. It would therefore be useful to have studies in which measures of slowing at several levels of cognitive processing were taken -- for example, measures of masking could be related to performance in situations requiring visual scanning, stimulus identification, and problem solving.

To close this section, we consider a more complex task. In visual scanning studies, the observer must locate a target figure in a field of distractors -- e.g., determine which lines have the letter "X" in the display in Figure 15. A large number of studies have shown that the elderly (age 60 and beyond) are slower than young adults in visual scanning (Rabbitt, 1968), and are more likely to be distracted by irrelevant information during scanning (Rabbitt, 1965). However, those studies that have included a middle aged group have typically not shown changes in scanning rates from age 20 to 50. While this makes it likely that the main changes in scanning rates occur after age 50, the available data are quite limited.

An implicit assumption of most scanning studies is that the observers are responding as fast as they can without making errors. In fact, though, people can trade off speed for probability of error. Thus an apparent slowing of scanning speed with age might reflect the adoption of a more cautious search strategy rather than a loss of the capability to scan rapidly (Pachella, 1974). Hoyer, Rebok, and Sved (1979) observed that individuals in their 40s and 50s were slower but more accurate in a visual sorting task similar to visual scanning. This results suggests that the middle aged individuals might have traded off speed for greater accuracy, perhaps because of a lower tolerance for errors. Older adults often appear intrinsically to prefer accuracy over speed in these kinds of experiments (Rabbitt, 1977), but a simple tradeoff probably does not account for all the speed differences in visual scanning when one compares early adulthood to the retirement ages.

There seems to be a difference beween the way that visual scanning studies are done in the laboratory and the way that visual scanning seems to occur in most practical situations. In the typical laboratory study, the observer is asked to scan a display and do nothing else. In field situations visual scanning is typically done in conjunction with other tasks. To illustrate, a motor vehicle driver continues to guide the car while scanning road signs. Rabbitt (1977,1979) has found that differences in the visual scanning performance of young and elderly subjects can be magnified either by increasing the number of distractors in a display or by introducing an ancillary (memory) task. This sort of result has lead several people to conclude that visual scanning demands "attentional resources", and that these resources are reduced with age (Rabbitt, 1979; Hasher and Zacks, 1979; see the section on Attention below). Rabbitt's results, which are not based on studies using middle aged subjects, suggest the need for further exploration of age changes in scanning performance when done in conjunction with other tasks.

Another indication that age changes properties of perception is the change in several visual illusions, such as the Muller-Lyer illusion. Comalli (1970) has reviewed a large body of data which suggests that older persons have illusions similar to young children -- that is, a "regression" of the perceptual illusion to pre-adult levels. However, most of the change appears to occur in the late 60's and 70's, and is not of paramount interest for this report.

One way of summarizing the results of the various studies on age and visual detection and identification is to consider what sort of tasks would be expected to reveal performance differences between people in their 20s and 40s. If the task required detection of rapidly moving targets, at low levels of illumination, younger observers should be markedly better, enough so that the difference might be of serious concern to equipment designers. If the task required rapid identification of single stimuli the younger observers might still be more rapid, but their advantage would probably be much reduced. If the task required that the observer pick out a clearly distinct stimulus from an array of stimuli of the same type, large age differences would not be expected. However, perhaps age effects would reappear if the scanning task were made more difficult or if it were to be done in conjunction with other tasks.

AUDITION

Hearing is exceptionally sensitive to age. Many changes in audition are associated with straightforward changes in the physiology of the inner ear; atrophy and degeneration of hair cells and supporting structures in the basal coil of the cochlea, atrophy of the stria vascularis of the scala media (leading to deficiencies in endolymphatic fluids) and atrophy of structures associated with cochlear vibration. Each of these changes might theoretically be associated with different types of loss of auditory sensitivity (presbyacusis). The cochlear changes should be associated with specific high frequency hearing losses that are characteristics of advancing age. Changes in the endolymphatic fluids should lead to a uniform loss in sensitivity at all

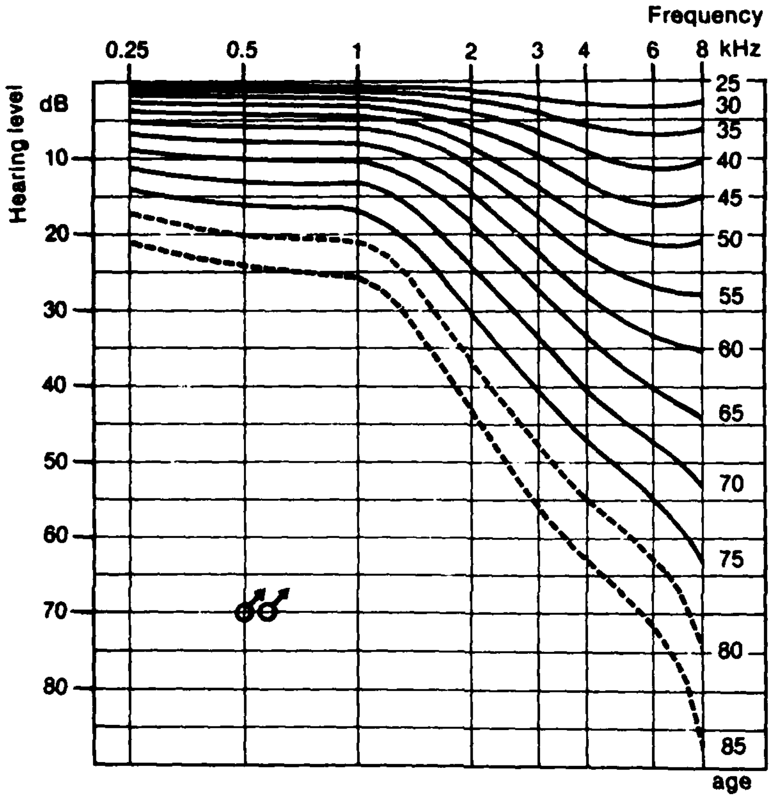


Figure 16. Hearing as a function of age and frequency: Data for men. (Spoor, 1967).

frequencies, combined with loudness recruitment, so that noisy situations should make fine discriminations harder. Changes in cochlear vibration should be associated with a graded loss of hearing from low to high frequencies. All these phenomena have been observed (Bergman, 1980; Corso, 1977). In addition, there are age related differences in hearing that are probably associated with central nervous system factors. Isolation of the central from the peripheral effects is an important, but difficult task. Speech perception is a good illustration. The understanding of speech seems intuitively to be a central process. A measured loss in speech perception cannot routinely be attributed to CNS deterioration, because peripheral changes may limit the quality of the perceived speech. To account for peripheral effects, studies of age differences in speech perception often speech perception after equating subjects for peripherally produced presbyacusis (Corso, 1977). However, it is not always clear that matching listeners on the perception of pure tones in a given set of frequencies (or any other single criterion) does in fact equate individuals, since they may differ in forms of hearing loss not tested by that criterion.

Age associated losses occur in the ability to detect pure tones by age 40, if not sooner, although very pronounced changes do not occur until somewhat later. Figure 16 shows that auditory sensitivity to pure tones declines exponentially from young adulthood, with the greatest loss at high frequencies. The largest declines are at higher frequencies than those critical for perception of normal speech (roughly 1000 to 2500 Hertz), but some age-related decline in the speech frequencies is observed. For an as yet unknown reason, the loss is less in women than in men. Corso (1977), in reviewing these data, states that beyond the middle 30's some hearing loss is evident in virtually all individuals. Bergman (1980) emphasizes the complementary side of the picture -- namely, that there are both individual differences and subpopulation differences in presbyacusis curves! We should emphasize then that the curve in Figure 16 is representative of average pure tone sensitivity for members of Western industrialized societies.

In addition to loss in detection, loss in discriminability of supratnreshold stimuli also occurs. Figure 17 demonstrates this, by showing pitch discrimination as a function of age and frequency (Konig, 1957). As was the case for detection, the loss is progressively greater as the frequency of the sounds increases. The loss of discrimination at the higher frequencies in Figure 17 is clearly evident in the 25 - 35 age range. The data from Figures 16 and 17 indicate that it may be necessary to screen middle aged personnel for hearing loss if analysis of middle to high frequency sounds (roughly, greater than 2000 Hertz) is an important aspect of their jobs.

While there are industrial situations in which tone detection and/or discrimination is important, speech perception is far more important. As Figures 16 and 17 show, there are losses of auditory capacity in the speech frequencies during the age interval 20-35. These become more marked later in life. The importance of these losses vary greatly with the conditions of speech perception. Bergman et al. (1976) determined speech detection in listeners whose age varied from 20 to over 70. Both longitudinal and cross-sectional data were taken, making this study one of the better designed ones in the literature. In addition to determining detection of normal speech, speech detection was determined under a variety of adverse conditions. A portion of the resulting data is shown in Figure 18. Three functions are shown, for age-related perception of normal speech, speech presented with a competing speech signal in the background, and speech that was interrupted electronically, as might be the case in a static-prone radio transmission. As can be seen from the figure, there is little interference with normal speech perception until beyond age 60. Somewhat more age-related decrement is shown in selective listening, and very marked decrements are shown in listening to interrupted speech. Corso (1977) suggests that much of the reduced speech perception with advancing age may be a function of increased time to process information in the auditory cortex. The peripheral changes discussed above probably contribute to the deficit also.

Bergman et al.'s experiment is an important one for two reasons. Conventional audiometric examinations determine pure tone frequency hearing loss, on the assumption that this correlates well with the perception of spoken words (Geldard, 1972). While this may be the case for the perception of single words in isolation, other factors may be involved in the perception of sentences under adverse listening conditions. Bergman (1980) suggests that high frequency hearing loss will in fact "generally create considerable difficulties in understanding speech heard under other than optimal conditions" (page 30). A recent study reported by Bergman (1980) emphasizes this point. Middle aged (ages 45 - 63) and older listeners had more difficulty understanding speech of talkers whose voice and speech patterns were rated as poor. Whispered speech was particularly troublesome. Bergman's explanation is that whispered speech reduces the amount of information available from glottal (phonatory) energy, placing greater import on the relatively high frequency information present in the formants and consonants.

Since many industrial situations do inevitably involve poor listening conditions, it would be advisable to determine whether or not defects in practical speech perception are identified by current audiometric measurement techniques and, if they are not, what new measurement techniques would be appropriate. A second point to keep in mind about Bergman et al's results is that, if anything, they may understate the seriousness of the situation. In the Bergman et al. experiments, listeners generally were required to report speech verbatim. If they had also been required to comprehend and evaluate that speech, the added

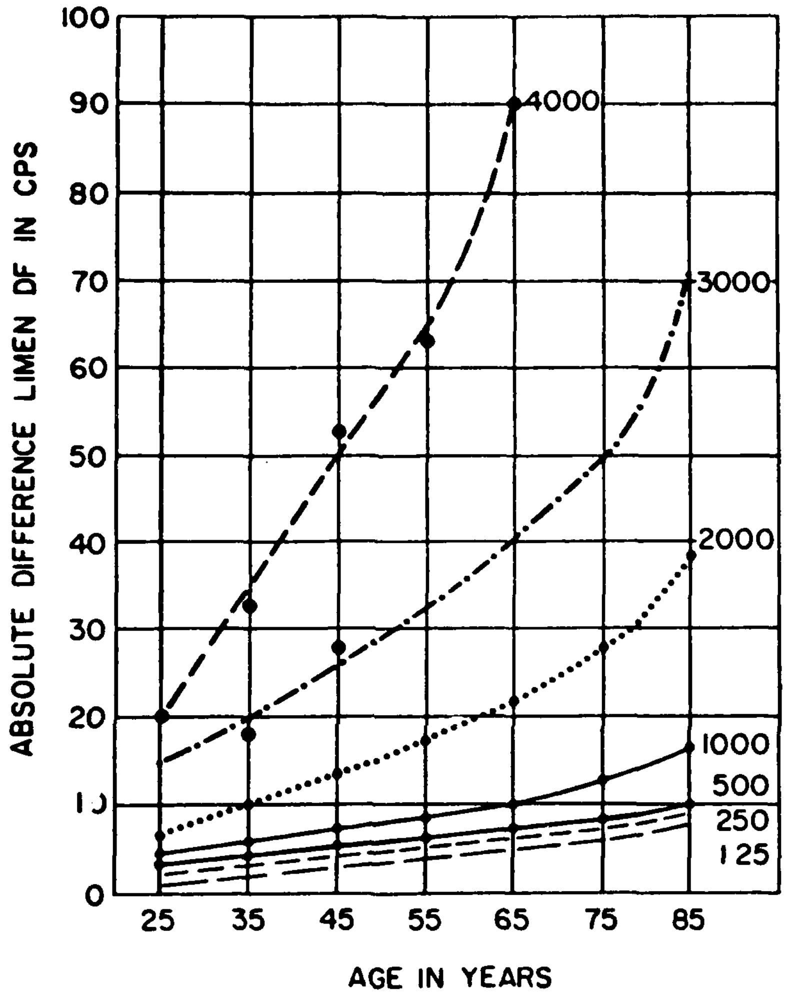


Figure 17. Threshold for detecting changes in pitch as a function of age and frequency. (Konig, 1957).

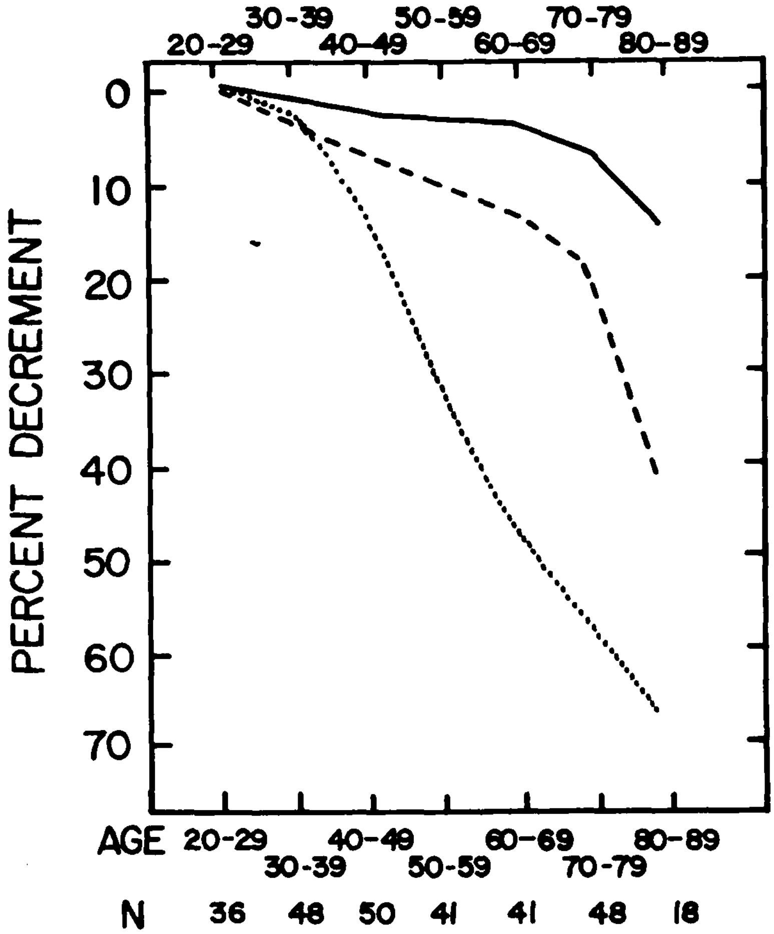


Figure 18. Speech intelligibility: Percent decrement from Age 20, as a function of age. Solid line-normal speech. Dashed line-selective listening in the presence of competing voices. Dotted line-speech interrupted 8 times/second. Data from Bergman et. al., 1976.

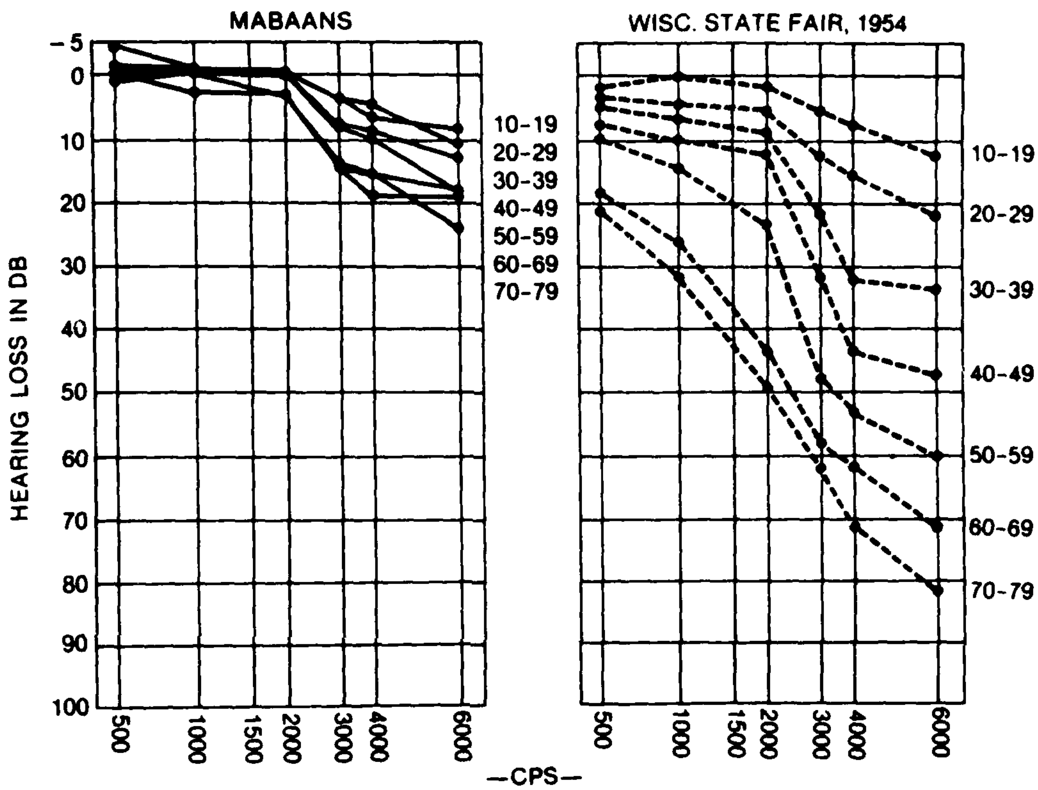


Figure 19. Hearing loss in Mabaan tribesman (Sudan) and Wisconsin Residents. From Bergman (1980).

processing requirement might have interacted with the attentional demands of the difficult speech perception task to produce even greater age deficits.

While certain changes in the auditory system are inevitably age-related, personal experiences are also strongly involved in the determination of adult hearing capacity. It is well known that enviornmental events, in particular exposure to intense, high frequency noises for a long period of time, can produce marked loss of hearing. Such situations are particularly common in an Armed Services environment. Whether or not environmental damage is additive to an age effect, or interactive, is not known. This probably depends upon the precise type of damage produced by the environment (Corso, 1977). Part of the differences in presbyacusis curves between populations of adults may be a function of environmental factors. The differences can be quite large. Figure 19 shows data for 2585 Wisconsin residents and 541 Mabaans, a group of Sudanese tribesmen. Note that the hearing loss in the Mabaans tribe is much smaller than the loss in the Wisconsin residents. The Wisconsin residents may be more representative of the population of American service personnel. More seriously, the data of Figure 19 illustrate dramatically how much of our "normal" aging trend may in fact be a reflection of our normal environmental hazards and personal health hazards.

Consistent with these findings, there is evidence that the U.S. population as a whole is becoming more hard of hearing. The rate of incidence clinical deafness in 1960 was approximately 300 per 10,000, up from under 200 per 10,000 in 1940. By the turn of the century the deafness figure is expected to reach 360 per 10,000 (Watson and Tolan, 1967). If we assume that the incidence of subclinical cases of hearing loss is proportional to the deafness figures, this means that there is a marked cohort effect, i.e. that the 30 and 40 year olds of tomorrow will have a greater incidence of hearing troubles than do people in this age bracket today. Part of this cohort effect might be related to personal habits -- Kryter (1970) has reported a high level of noise-related deafness and hearing loss in rock musicians! The impact of the increasing incidence of major hearing loss upon industrial performance should be investigated.

Inexplicably, there are no studies in the literature of age changes in the speed and integrity of auditory information processing analogous to the studies in visual information processing reported in the preceding section. For example, we do not know how the process of information readout from echoic memory (the auditory equivalent of iconic memory in vision) is affected by aging (Crowder, 1980). Since the organization of auditory cortex and related pathways in the brain differs from the organization of the visual centers (e.g., there are more primary cortex areas devoted to audition than vision), we should not assume that age changes in the two systems would be strictly identical.

COMMENT ON SENSORY CAPACITIES AND AGE

Many of the sensory detection and discrimination studies currently in the literature have relied upon a person's ability to detect a stimulus, assuming that all individuals use the same criterion for detection. If there is a systematic shift in criteria with age, in the direction of demanding a higher criterion signal before responding, then increases in "caution" would appear as decreases in sensory sensitivity. A limited amount of evidence suggests that this is indeed a possibility (Craik, 1969; Rees and Botwinick, 1971). While it seems unlikely that a repetition of the studies we have reported using criterion-free methods (e.g., Signal Detection Theory approaches) would eliminate the age effects, the magnitude of the estimated age change might be reduced. If it were the case that some of the age changes were indeed a function of the observer's criterion, then middle aged personnel could be trained to increase their frequency of false alarms to adjust for cases where a missed signal would have a high cost.

Studies demonstrating defects in simple detection of stimuli are apt to be dismissed with the comment that there are obvious prosthetic measures. Eye glasses are common in our society. It is much harder, however, to remedy perceptual and sensory defects that are associated with accomodation to ranges of stimuli; e.g. rapid shifting of the gaze from far to near and back again, or filtering a signal through noise in a speech perception task. While the typical man or woman in the 40's is neither blind nor deaf in the clinical sense, drops in the sensitivity of vision and hearing in this age range are large enough to warrant study of how they affect performance in demanding work environments.

In this section our focus has been on sensory and primitive perceptual processes, to the exclusion of more complex processes of stimulus analysis and response production. Although the interaction between sensory and higher order cognitive processes has been little studied, it may be quite important both theoretically and practically. We shall argue below that higher order cognitive functioning demands attention, and that one of the characteristics of older individuals is reduced attentional capacity. In younger individuals, adequate sensory perception may proceed almost independent of any allocation of attention, whereas the older individual may achieve the same level of sensory perception only by actively attending to the stimulus channel. Primitive acts of perception become competitors for attention for the older person in a way that they are not for the younger. Thus an older person who, with effort, could pass a test designed to evaluate sensory functioning and nothing else, might not be able to function in a job that combined sensory perception with more complex tasks.

Minor sensory problems can lead to psychological discomfort, even if they do not affect job performance directly. Among the elderly there is clear evidence of emotional disturbance associated with sensory loss, especially when that loss affects functioning in intellectual situations (Corso, 1977). Whether minor problems, such as irritability, would be characteristic of middle aged individuals working in noisy or low vision environments is a matter for speculation. As the success of the volunteer services depends heavily upon attracting these individuals to military careers, and keeping them in those careers, some thought should be given to changes in working situations that can avoid such problems.

5. THE CAPACITY TO ATTEND

In studies of visual and auditory capacity, it is implicitly assumed that the individuals being evaluated are giving their full attention to the test stimulus. The assumption is probably correct, because testing situations are simple (e.g. a listener may be asked if he or she hears a tone) and because testing sessions are brief. When more cognitive abilities are being examined, as in studies of memory or problem solving, care must be taken to control a subject's allocation of attention to various aspects of the task. Attention allocation is also of considerable practical interest. Many accidents are "explained" by saying that the people involved failed to attend properly. There is also a great deal of anecdotal evidence suggesting that the ability to control attention decreases with age. Most of the anecdotes have to do with inattentiveness in old age. Less is known about changes in attention as people move from their twenties to their sixties. Clearly the average person of thirty or forty does not lose the ability to concentrate to the point that inattentiveness becomes a personal problem requiring professional help. As was pointed out in the introduction, a small decrement in a psychological function may be trivial to an individual but important on a population basis. Given that changes in attentiveness are observed in the elderly, it is reasonable to ask whether or not minor changes in attentiveness can be observed during the working years.

This question is hard to answer. Attention must be measured indirectly, by observing performance on tasks that require attention, but that also draw on other psychological functions. To illustrate, suppose that someone has a notoriously poor memory for peoples' names. Is this because the individual does not pay attention when introduced to strangers, or because the person's perception is deficient, or because the person finds it hard to store and retrieve information? More particularly, because it is reasonable to believe that people lose some ability to control attention as they age, a number of experiments on memory, problem solving, and decision making have been "explained" by assuming a loss of attention. We shall argue below that this conclusion is warranted only in fairly limited circumstances. Furthermore, if the concept of "loss of attention" is to be appealed to as an explanation of experimental results, one has to define what attention is. No satisfactory definition has been offered.

The remainder of this section discusses some of the conceptual and methodological problems involved in determining a person's ability to allocate attention to information processing tasks. Although some experimental results will be cited, the thrust of the argument is theoretical. The major purpose of the section is to introduce concepts about attention that will be important when we deal with the relation between age and higher cognitive functions such as memory and problem solving.

THE ATTENTIONAL RESOURCE MODEL

One way of conceptualizing attention is to take the notion of "paying attention" quite literally, by imagining that we have a finite amount of attentional resources. An attention demanding task is one that requires the expenditure of resources from this supply. Kahneman (1973) has presented this idea in some detail. In his view, any mental task requires the activation of mental structures. These are the mechanisms that accomplish the functions required to do the task, such as discrimination of objects, rehearsal of information in memory, and the manipulation of visual images. Each of the structures draws upon the pool of available mental resources. The pool itself is termed attentional capacity. A structure will increase its demands upon attentional capacity if the information processing load on the structure is increased. Similarly, the greater the amount of resources provided to a structure when dealing with a fixed information processing load, the more rapidly and accurately the structure will perform its task. Complex tasks, such as reading a novel or driving an automobile, require the coordinated activation of several structures and an appropriate allocation of attentional resources to each of them.

Consider some abstract task that involves one or more mental structures. The function relating overt performance to the amount of attentional resources allocated to those structures required by the task is called the performance-resource function. The performance-resource function is unobservable in principle, because "attentional resources" refers to an abstract concept rather than a measurable expenditure of energy. In spite of its purely conceptual nature, the performance-resource function may be used to classify tasks by their resource demands. Norman and Bobrow (1975) define resource-limited tasks as tasks on which the performance function is strictly monotonically increasing, i.e. tasks on which performance levels increase with an increase in the amount of resources allocated to the task. Not all tasks are resource limited, and a single task may be resource limited under some conditions and not resource-limited under other conditions. Take the case of a person listening to the radio under poor reception conditions. Accuracy of reception will depend partly upon the attentiveness of the listener. At a certain point, though, concentrating harder simply will not further improve reception. Asymptotic performance will depend upon the physical nature of the stimulus, as filtered through the listener's auditory apparatus. Maximum accuracy may be reached without the listener devoting complete attention to the signal, to the exclusion of all other stimuli. In such a case performance is said to be "data-limited." The term implies that performance is limited by characteristics of the external stimulus but, as the example shows, a data limitation may also be imposed by the character of a person's sensory or mental structures. For instance, in consideration of the data reviewed in the preceeding section, presbyacusis might impose a data limitation on the auditory task performance of older adults, even though younger adults were resource limited under the same conditions.

One way to think of the alleged inattentiveness of older adults is to assume that attentional capacity decreases with age. This will be referred to as the "attentional deficit hypothesis." If the hypothesis is true, performance should decrease with age whenever people are devoting full attention to a resource limited task. While this inference is conceptually straightforward, it is difficult to construct a practical test of it. The problem is that one cannot be sure that maximum performance is determined by a resource limitation rather than a data limitation. Consider, for example, the study of the speed with which people do mental tasks, varying from simple choice reaction time studies to reasonably complex mental arithmetic. Almost every study of age effects in such tasks has shown a decrease in speed of mental performance with advancingg age. The decrease is evident by the thirties and forties (Birren, 1974; see also the discussion of specific tasks given in the following sections of this report). Furthermore, the decrease cannot be accounted for by changes in motor capability, because the amount of age-related slowing is related to the psychological complexity of the task rather than to its motor components (Cerella, Poon, and Williams, 1980). It is also true that under certain circumstances speed of mental performance is a reasonable indicator of the amount of attentional resources allocated to a task (Kahneman, 1973; Posner, 1978). Thus, although one interpretation of the observed slowing is that attentional capacity decreases with age, this conclusion is not dictated by the data. Slowing could easily be due to structural changes in the centeral nervous system, such as demylinization of nerve fibres or a reduction in the number of neurons in the brain. More generally, the fact that changes in the speed of individual performance, across conditions of an experiment may reflect changes in attention allocation does not mean that changes in inter-individual performance in the same experiment are due to inter-individual differences in attentional capacity.

An alternative way of evaluating the attention deficit hypothesis is to restrict the amount of attention that a person can allocate to a task. This is done by introducing a new task that is to be performed on a high priority basis. The original task then must be done with a person's "spare capacity". This is defined as the attentional resources that a person has remaining after allocating enough attention to reach a satsifactory performance level on the primary task. The technique of evaluating spare capacity by considering primary and secondary tasks is called the "secondary task paradigm." It is a special case of a "dual task situation", in which people are asked to perform two tasks more or less concurrently. The conceptual argument for the secondary task paradigm is straightforward. Imagine two people, A and B, both of whom have sufficient attentional capacity to achieve maximum performance on either of two tasks, 1 and 2, when done alone. If the two tasks are done together, the joint demands of the tasks may exceed the attentional capacity of person A but not person B, making it possible to discriminate between them. If the attention deficit hypothesis is true, older individuals should show a greater decrement in performance than should younger people when moved from a single to a dual task situation.

While the observation that older individuals have trouble with dual task situations would be consistent with the attention deficit hypothesis, alternative explanations are possible. The secondary task paradigm was originally developed as a way of measuring the attention demands of the primary task (Kerr, 1973). The reasoning was that if the secondary task is resource limited, then the attentional demands of two primary tasks can be compared by observing how great a decrement occurs on secondary task performance. This argument assumes that the secondary task is resource limited, and that the primary and secondary tasks do not compete for mental structures. When the secondary task paradigm is used to study individual differences in attentional capacity, some more complicated restrictions must be met. Basically, these have to do with the pattern of correlations between performance on the two tasks, both alone and in combination. It is also necessary to observe primary task performance at two levels of difficulty (Hunt and Lansman, 1981).

There have been several reports of age related decrements in performance in dual task situations, including a few studies that have used the secondary task paradigm. In interviews with experts in gerontology we have found that there is a strongly held belief that dual tasks become exceptionally difficult as one grows older. Data from studies of dichotic listening are cited in support of the thesis. The participant in a dichotic listening task hears two messages, presented simultaneously, one to each ear. After the messages are completed the participant is cued to report the message from one ear, and then the message from the other. The

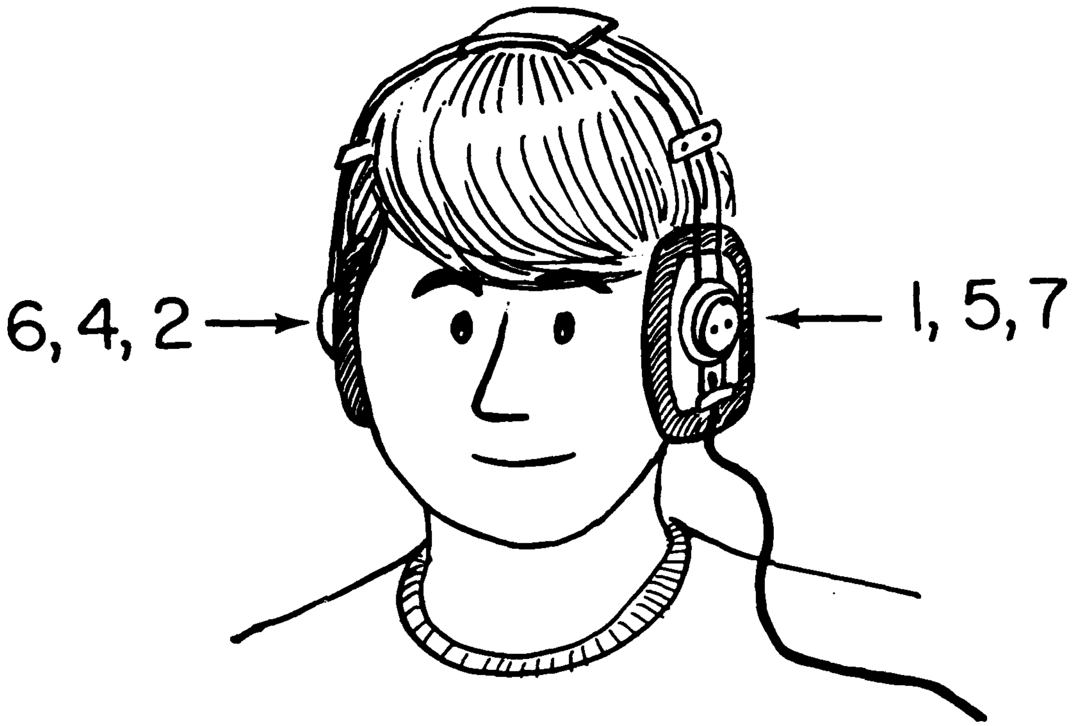


Figure 20. Dichotic listening task. After hearing digits in each ear, listener tries to recall one set of digits, then another.

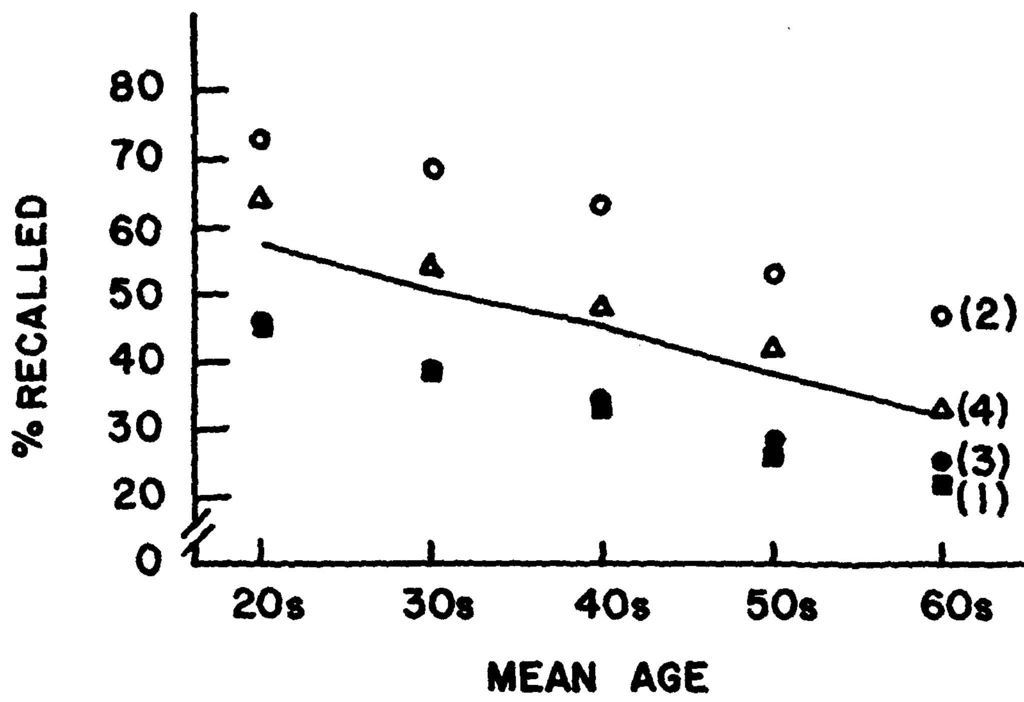


Figure 21. Recall of signals from secondary task in dochotic listening studies. Data from four independent studies (Barr, 1980).

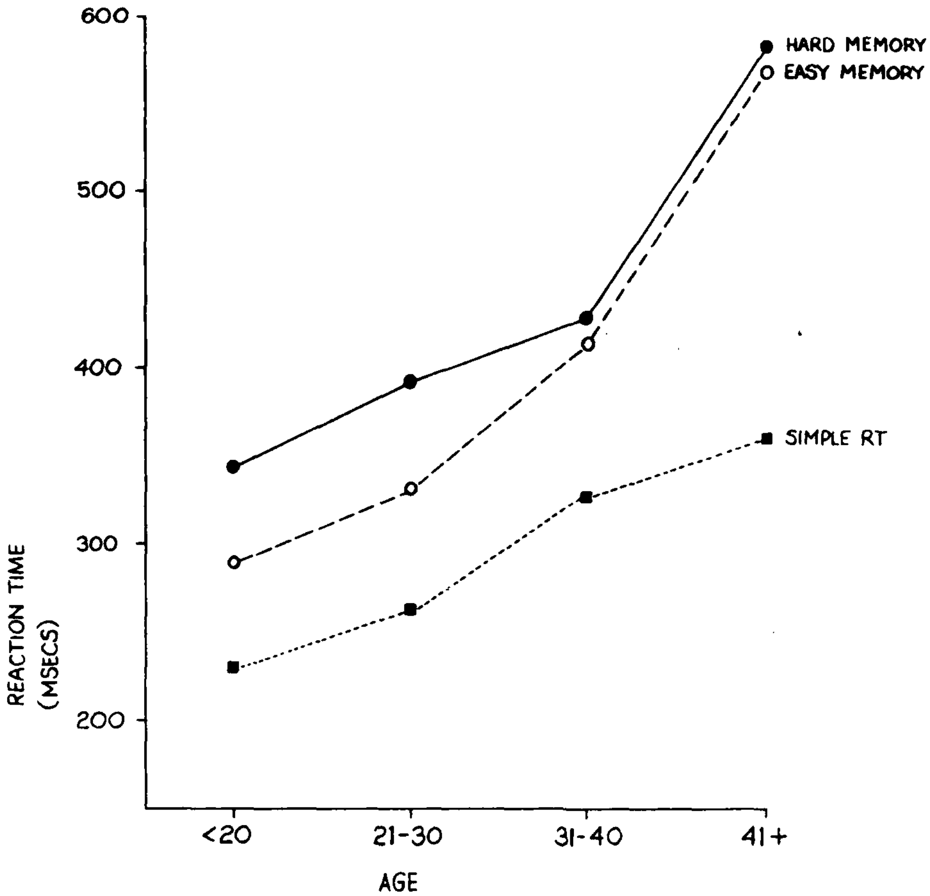


Figure 22a. Reaction time to probe tone alone (simple RT) or in the presence of easy or hard memory tasks. Verbal Memory Task. (From Hunt and Lansman, 1981).

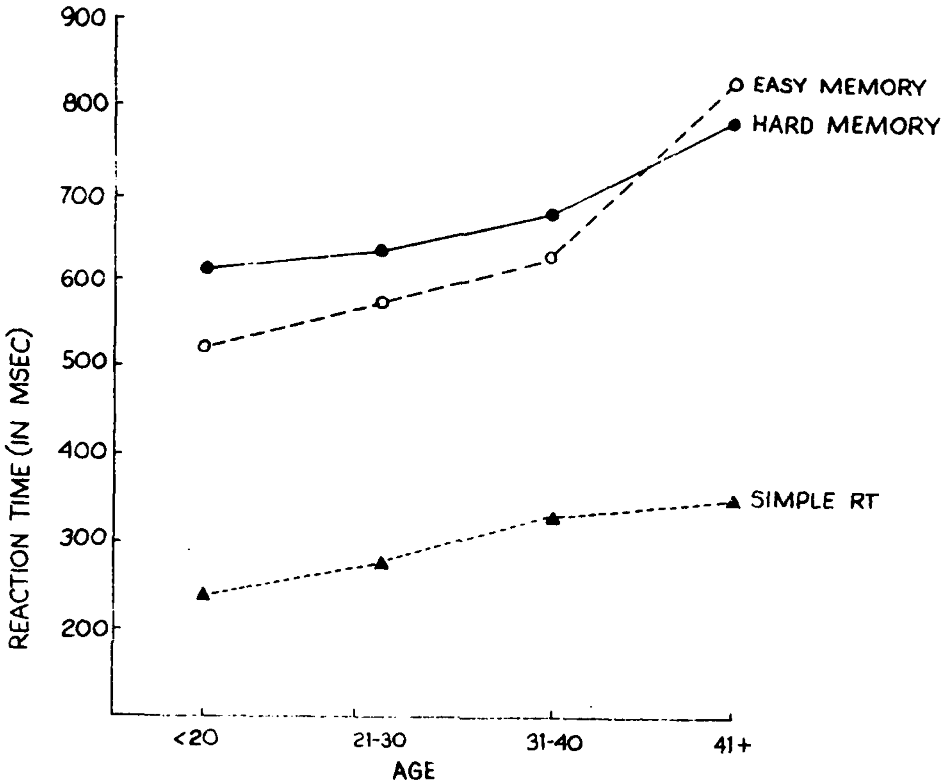


Figure 22b. Reaction time to probe tone alone (simple RT) or in the presence of easy or hard memory tasks. Visual Memory Task. (From Hunt and Lansman, 1981).

paradigm is illustrated schematically in Figure 20. Note that the order in which the messages are to be reported is not indicated until after the messages have been received. The conclusion that is typically cited is that there is an age related decrement in the ability to recall the message reported second, but not in the ability to recall the message reported first. This has been explained by saying that older individuals are unable to retain the second message while reporting the first. Such an explanation is consistent with the attention deficit hypothesis, as it is well known that short term recall depends upon the attention that a person devotes to retaining information in working memory.

There are two problems with this conclusion. One is that the experiment does not rule out the possibility of structural interference. If articulatory structures are required for the maintainence of verbal information in short term memory, one would expect first message recall to interfere with second message recall because of competition for a structure rather than because of competition for a generalized attentional resource. This is a reasonable hypothesis because there are data suggesting that subvocal rehearsal is required for verbatim recall of information held in short term memory (Baddeley, 1976). A second objection, which is somewhat stronger because it does not depend on a theoretical interpretation, is that the data are simply weaker than the statements in the secondary literature would lead one to believe. Figure 21, adapted from Barr (1980), shows the average number of digits recalled in a dichotic listening study, as a function of age and order of report. While the age effect is larger for recall of the message reported last, the discrepancy between age effects on first and second message recall is not striking.

Hunt and Lansman (1981) conducted a series of experiments that were specifically designed to evaluate individual differenes in attentional capacity by use of the secondary task paradigm. Here we report an additional analysis of their data (not included in the original report) because it directly addresses the attention deficit hypothesis. The tasks performed by Hunt and Lansman's subjects were (a) a memory task and (b) a simple response to a probe tone. The memory task involved either verbal recall or visual recognition, and could be presented in either an easy or a hard version. As the memory task was always designated to be the primary task, one would expect the response to the probe tone to be delayed in the secondary task condition. The amount of the delay should be related to the difficulty of the primary memory task. Now consider how age should affect the picture. According to the attentional deficit hypothesis, older individuals, with smaller reserves of attentional capacity, should show a greater decrement in their response to the tone as the memory task becomes harder. Some relevant data are shown in Figure 22. The expected interaction between age, response to the tone, and single and dual task condition does occur. The results are in accord with the attentional deficit hypothesis.

AUTOMATED AND CONTROLLED RESPONDING

It has been claimed that when a person has had a great deal of overlearning on a task it becomes "automatic", and no longer demands on attention. The argument has been made most strongly by Schneider and Shiffrin (1977), who designed a paradigm for "developing automaticity" in a visual scanning task. From the viewpoint of an observer, the task is as follows:

(1) A target set of letters is exposed, for example,

X A

(2) A frame is exposed. The frame consists of from one to four letters, as in

R S
Q A

The observer's task is to determine whether or not the frame contains any member of the target set. Thus in the example the correct response is "Yes" because there is an A in the frame. The dependent variable is either the minimum time that the frame can be exposed in order to produce reliable identification of targets, or the time required for an identification, if frame exposure time is unlimited. Either dependent variable can be used to estimate the time required to scan a display, as a function of the number of items in the target set and in the frame are varied. Two training procedures are used. In the consistent mapping (CM) training procedure the same target characters are used on all trials, and a character that is a target on one trial is never used as a distractor on another trial. After literally thousands of training trials, performance becomes almost independent of both frame size and target set size. Performance is then said to be automatic. In the varied mapping (VM) training procedure a character may be a target on one trial and a distractor on another. After training performance stabilizes reaction time becomes a linear function of the number of items in the frame and target set, suggesting that the observer conducts a serial scan matching targets against frame items. Performance is said to be "controlled", and to demand attention.

Note that automatic processing could be considered to be a logically degenerate case of controlled processing in which the serial search is carried out at infinite speed, producing a linear relation between performance and the number of characters in the two sets, but with zero slope. In practice pure automatic processing is not observed, but the slope of the linear relation may reduce to as little as 10 milliseconds per character. This represents a roughly ten to one reduction in slope from the beginning to the end of CM training.

According to the attention deficit hypothesis, age differences in visual scanning should be eliminated by CM training, because automatic scanning would not require attentional resources. In the pure case this is something of a tautology, because if pure automatic responding were to be achieved by all subjects their performances would all be described by functions with a zero slope. In practice, the question has been reformulated. Is asymptotic scanning performance related to age after CM training?

Two experiments indicate that it is. Madden and Nebes (1980) gave eight daysof CM training to old (beyond 60) and young subjects. On the ninth day the slope of the linear function was 25 msecs for the young subjects and 63 milliseconds for the older ones. Thus the groups were different in terms of the absolute value of the critical variable. Neither group reached true automatic performance (although the younger group reached a value close to that found in most studies). Both groups displayed a roughly eight to one reduction in slope from the first to last day of CM training. In an experiment in our own laboratory, we replicated these results, using an auditory scanning task that had previously been shown to produce automated responding (Poltrock,Lansman, and Hunt, 1981). We also used subjects in the 20-60 age range. Thus the Madden and Nebes' findings concerning asymptotic performance appear to generalize both to a wider age range and to auditory as well as visual scanning. At face value the age difference in asymptotic "automated" performance is an argument against the attention deficit hypothesis. On the other hand, one could argue that the problem is not with automaticity per se, but rather with the development of automaticity. It might be that given a fixed number of trials, older people do not move as far toward automatic performance as do younger ones. The essence of the argument revolves around one's choice of operational definition for automaticity. Neither the Madden and Nebes nor our own experiment met this criterion. If the definition is (approximately) zero slope, then equality of performance is guaranteed, if all groups can be trained to reach this criterion. If the definition of automaticity is the reduction of attentional demands by some amount defined relative to initial performance, or if automaticity is defined solely by reaction to a fixed amount of training, then it does appear that age differences remain after CM training. Whether this is due to age-related change in the asymptotic form of the performance-resource function or due to age-related change in the acquistion of automated responding does not seem to be a resolvable issue.

A slightly different approach to the question of age related differences in automated performing is illustrated by the work of Hasher and her colleagues (Hasher and Zacks, 1979; Attig and

Hasher, 1980). On the basis of other evidence, Hasher et al. argue that certain types of learning, notably memorization of the order of events or recall of lists of items, require controlled processing, while learning either the relative frequency of two repetitively experienced events (e.g. the relative number of times you have seen two TV commercials) or recording the relative age of an event (continuing the example, which of the commercials was seen most recently) is an automated event. Using an experimental analog of this example, Hasher and Zacks showed that tasks that were presumed to require controlled learning did indeed show differences in performance between elderly and young adults, while tasks requiring automated learning did not. Hasher et al. interpret their results as support for the attentional deficit hypothesis. While the results are certainly consistent with the hypothesis, they require a specific interpretation of frequency and relative age learning.

The activation of semantic associates another automatic process. For example, a variety of experiments have shown that requiring a person to name or identify words such as CAT, DOG, etc. will increase their speed in identifying related terms, such as WOLF and HORSE. The effect is referred to as semantic activation, and has been shown to be an involuntary process (Posner, 1978). Young and elderly adults both show semantic activitation effects, as reflected by priming of reaction times to words preceded by an associate (Howard, McAndrews, and Lasaga, 1980). There is therefore no reason to believe that this type of activation changes over the working years.

THE CONTROL OF ATTENTION

The term "attention" is sometimes used to refer to control of attention, as in selective attention to one source of signals instead of another. This is a somewhat different concept of attention than the view of attention as a pool of mental energy. Two types of controlled attention can be conceptualized, the ability to attend to one source of signals while ignoring another source (selective attention) or the ability to monitor two sources of signals at the same time (divided attention). In order to determine whether one or two attention allocation abilities should be assumed, Poltrock, Lansman, and Hunt (Note 7) had subjects perform auditory and visual tasks in which signals were presented on two "channels", either by dichotic auditory presentation of words or by displaying characters at two different locations in the visual field. In control conditions, signals were presented on only one channel. A factor analysis indicated that different abilities were involved in monitoring auditory or visual signals, but that the same ability underlay performance in the selective attention and monitoring conditions. Poltrock et al.'s subjects ranged in age from their 20s to their 50s. Age was negatively correlated with performance in both the auditory and visual conditions, although the size of the relation was modest (r about .25). This would be expected simply because of the well known deterioration of the auditory and visual systems over the adult life span. The magnitude of the age-performance correlations were no higher in the more difficult selective attention or monitoring conditions than they were in the control conditions. This result is not consistent with the attentional deficit hypothesis, which would predict higher correlations with age in situations that tested individual attentional capacity limits.

SUMMARY

The attention deficit hypothesis probably is a good heuristic for predicting the performance of elderly (over 60) individuals. It seems less useful as a scientific model for the analysis of work performance of adults in the 20-60 age range. In spite of claims in the secondary literature, the magnitude of age related "attentional defects" appears to be small unless one wishes to equate speed of performance with attentional capacity. This is discussed in more detail in the following chapter.

More seriously, the status of attention as a scientific concept is unclear. Kahneman's (1973) approach, in which attention is viewed as a single mental resource, fits well with the attentional deficit hypothesis. There are other views. One is that there are multiple pools of attentional resources, and that different tasks draw upon different pools (Navon and Gopher, 1979; Wickens, 1979). Another view is that any performance decrement that occurs during dual task performance is due to competition for structures. Dual tasks that are not highly overlearned are bound to compete, because both require extensive working memory space so that the performer can monitor the external world as the imperfectly learned task is being executed. If a task is sufficiently practiced, the need to monitor task-relevant stimuli is reduced, and performance is "automated" because structural conflict for space in working memory no longer occurs (Allport, 1980).

Given the conflicting theoretical analyses and the absence of definitive data, what can be said? It seems most appropriate to take a pragmatic position. Different occupations place different demands on attentional capacity, intuitively defined. Airplane pilots are usually pointed to as examples of people who monitor many signals in high demand situations, college professors are said to be single-minded. There will be specific situations in which an analysis of attentional demands may help in understanding the interaction between age and performance. Such analyses will require that techniques be developed for measuring attentional demands in the situation of interest. It would be naive to expect that one could develop a single measurement procedure to serve as an "attention meter" universally applicable to all tasks and individuals. Indeed, if there are several different types of attentional resources, or if attentional resource conflict ultimately reduces to competition for specific mental structures, the goal of developing an attention meter is itself unreasonable.

6. RESPONSE SELECTION

This section discusses the relation between age and performance in a class of tasks that will be referred to as "response selection" situations. As any performance involves some response selection, further explanation is required. The tasks under consideration all require that a fairly simple motor movement be made in response to a clearly perceptible signal. A prototypical response selection task is shown in Figure 23. This figure shows an observer sitting in front of a panel that contains four lights and four buttons. Whenever one of the lights comes on, the observer is to depress the button immediately below the light. On a given trial, the following sequence of events might take place:

(1) The observer depresses a home button (button A in the figure), to indicate that he/she is ready for the trial to begin.

(2) The light above button A comes on, indicating that a stimulus is about to be presented.

(3) One of the lights above buttons 1 through 4 comes on.

(4) The observer moves his/her finger from button A toward the button under the light that was turned on at step (3). Call this the "target button".

(5) The target button is depressed.

This sequence can be modified. If the observer controls the beginning of the trial (step (1)) the experiment is referred to as being "self paced", since the observer controls the intertrial interval. In some studies step (1) is omitted, so that the experimenter controls the intertrial interval. In this case the experiment is said to be "experimenter paced", and the speed of pacing may be varied. In a few cases step (2) is omitted, and the trial is initiated immediately after the observer indicates that he/she is prepared. The interval between step (2), the warning signal, and step (3), presentation of the test signal, is referred to as the warning interval. The time between step (3) and step (4), the beginning of movement of the finger or hand, is referred to as initiation time. The interval between step (4) and step (5) is called movement reaction time (MRT). Initiation time is sometimes referred to as simple reaction time (SRT) if there is only one possible test signal (e.g., only one light in the schematic of Figure 23) and as choice reaction time (CRT) if there are two or more possible signals. In many experiments step (4) is

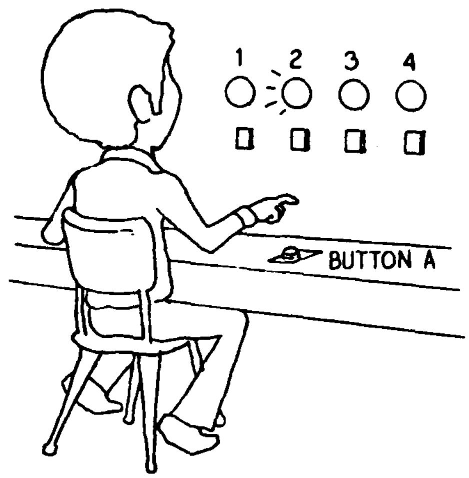


Figure 23. Choice reaction task. The observer moves his/her finger from button A to the button under the lighted lamp.

not recorded, so that the dependent variable becomes the reaction time between events (3) and (5), i.e. the sum of initiation and movement time. In this case the dependent variable is called SRT or CRT, depending upon the number of different signals that might have occurred.

The display panel used is often slightly different than that shown in Figure 23. Instead of having k locations for a signal there may be only one location, often a cathode ray tube or picture screen. The subject is told in advance which stimuli might appear, and instructed to make an identifying response to each of them. For example, an observer might be told to throw a joystick to the left if the figure "<-" was displayed, and to the right if the figure "->" was displayed. This would be called a choice reaction time (CRT) study with compatible stimulus-response matching, since the response required coincides with a usual interpretation the meaning of these figures. If the stimulus-response mapping were to be reversed, so that the joystick was to be moved left in response to a right pointing arrow, the experiment would be said to have an incompatible stimulus-response mapping.

The logic of the CRT paradigm can easily be extended to apply to auditory, tactile, or olfactory cues.

Obviously the CRT paradigm could be amplified to become a test of either perceptual or complex cognitive capacities. For instance, two lines might be displayed in a panel, with the subject being instructed to press a button on the side of the longest line. If the lines differed only slightly in length, this would be a test of speed of perception. Alternatively, an integer might be displayed, with the subject being instructed to move a joystick to the right if the integer was a prime number, and to the left otherwise. In this case reaction time would become a measure of speed of rather sophisticated mental arithmetic. All the reaction time studies to be described in this section involve situations in which the stimulus is immediately perceptible, its interpretation is trivial, and the major task is response selection. Situations involving an evaluation of the stimulus prior to the response will be considered in the next section.

Why study response selection? Response selection is a face-valid analog of a number of situations involving machinery operation and/or the monitoring of display panels. For this reason, response selection paradigms are sometimes included in test batteries for selecting equipment operators, including aviators. Response selection has been held to be of theoretical interest because it epitomizes choice behavior, which some think to be a basic step that underlies complex reasoning. The theoretical argument is valid if the mental processes underlying response choices are indeed analagous to those choice processes involved in reasoning and problem solving. One could argue either way, as the data does not conclusively confirm or deny the hypothesis. Jensen (1980) has reported several experiments indicating that groups of people who obtain high intelligence test scores make choice reaction responses more rapidly than do samples from low scoring populations. Movement reaction time, on the other hand, does not appear to differentiate high and low scoring groups. Work in our own laboratory has produced mixed results. In some studies CRT has been found to be correlated with scores on both verbal and non-verbal intelligence tests (r of approximately -.3, high scores being associated with fast responding). Other experiments have failed to locate a reliable association between CRT and intelligence test scores (Hunt, 1976; Lunneborg, 1977; Palmer, MacLeod, Hunt, and Davidson, Note 8). While we stop short of endorsing some of the more extreme claims that have been made concerning CRT paradigms as basic techniques for revealing mental processes, it is clear that these simple tasks have a substantive cognitive component.

There is an extensive literature on the relation between age, MRT, SRT, and CRT, and several reviews have been written (Birren and Welford, 1965; Welford, 1958, 1977). The most recent review by Welford (1977) is particularly relevant, and many of our comments are based upon his analyses.

It is clear that response selection slows with age, and that the slowing is due to the central processes involved in initiation time (SRT and CRT) rather than the motor responses involved in MRT. (Salthouse (1976) has observed that fine motor movements exhibit only a small amount of slowing over the working years. Large motor movements and movements that depend upon cardio-vascular functioning, such as running, are more affected.) Welford (1977) offers a particularly cogent argument for this conclusion. Consider a task in which the person simply taps on a target. Such a task consists solely of MRT, as there is no signalling stimulus. Provided that the individual is reasonably healthy, there is little increase in tapping rate from age 20 to 60. Quite different results are obtained using the simple reaction time (SRT) paradigm, in which the hand is moved from the home position to a fixed target, on demand. Reaction time (RT) increases by about 50% from the 20s to the 50s. Furthermore, the increase is almost entirely due to an increase in SRT rather than MRT. This clearly indicates that central rather than peripheral factors produce the aging effect.

Age effects are also pronounced in CRT studies, where the subject must select the appropriate response. Furthermore, performance on CRT tasks is related to performance in other psychomotor tasks. This was shown in a study by Robertson-Tchabo and Arenberg (1976). Healthy adults ranging from their 20s to their 60s were tested using a variety of simple motor, attention demanding, and perceptual tasks. The battery included tasks similar to the prototypical CRT task described above. When results were factor analyzed, the first factor was a "choice reaction time" factor, identified by the CRT task. The relation

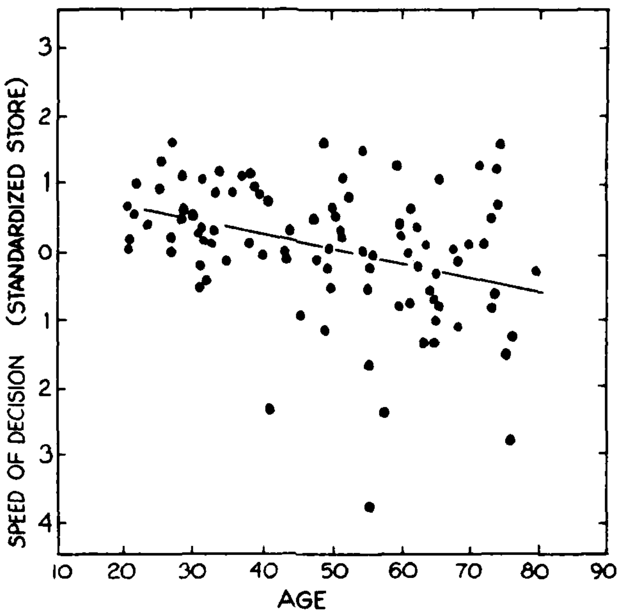


Figure 24. Score on a choice reaction time factor as a function of age. (Robertson--Tchabo and Arenberg, 1972).

between an individual's age and the score on this factor is shown in Figure 24. Speed of response selection clearly declined with age, a result found in numerous other studies. Individual differences were pronounced. Quick 60 year olds in Robertson-Tchabo and Arenberg's study performed as well as most of the 20 year olds. Conversely, there were slow younger persons whose performance approached the average performance of much older individuals. Note especially the increase in individual differences with age.

The data from choice reaction time studies are often summarized by the equation

$$\text{(4)} \qquad CRT = A + B\,(\log_2 N),$$

where A and B are positive constants, and N is the number of possible responses. Equation (4) expresses the fact that $\log_2 N$ is the average number of decisions that would be made, across trials, by a responder who was following a perfect decision strategy in selecting a response (Garner 1962). Thus an interpretation of Equation (4) is that B represents the additional time required for each added decision, while A represents the effect of all mental and motor responses that do not depend upon the number of alternative responses available. Under this interpretation B reflects purely central, decision making processes, while the value of A reflects both peripheral and central processes. If one of the effects of aging is to slow central decision making processes, one would expect to find age effects in the (entirely central) B parameter as well as on the value of A.

The empirical results are not this precise. Experiments on CRT almost always show age effects on A, and only sometimes on B (Welford, 1977). However, Birren (1965) cites several studies of reaction time which he interprets as ruling out age changes in peripheral movement time as the primary source of age changes in choice RT. Most other commentators agree with his conclusion. There is no contradiction, because the A and B parameters might respond to different central processes. Just what these might be is not clear at present. Birren has speculated that changes in the B parameter are due to minor cardio-vascular problems, resulting in a decreased supply of blood to the brain (Birren, Woods, and Williams, 1980; see also Szafr[illegible] 1968). If correct, this speculation would be of interest both for theoretical reasons -- why should cardiovascular deficiencies produce a selective effect on one aspect of decision making and not another? -- and for practical reasons, because CRT might be used as a behavioral index of minor brain damage. At the present time there is insufficient data to support or confirm the hypothesis.

Self paced CRT experiments allow the subject to determine the rate at which responses must occur. It is widely held that if people are forced to make rapid responses age effects will be increased (Welford, 1977). The evidence for this assertion is rather weak, especially for subjects under age 60. Figure 25, shows performance on a paced and unpaced tracking task. Although this data has been cited as evidence indicating that paced responding is difficult with advancing age, the situation appears more complex. Performance increases with age in self paced responding, up through the 40s. It remains constant over the same period if the responses are experimenter paced. Beyond the working years there is a decline in responding, but the decline due to age is additive to the decline due to pacing itself. These findings hardly support the fairly widely held belief that workers in their forties or fifties should not be given rapidly paced tasks. On the other hand, industrial surveys do indicate that when given free choice, older workers avoid paced tasks. (Interestingly, they do not avoid situations involving heavy physical labor). Since the question of responding to situational pacing is important in some industrial applications, the topic should be given further study.

Introducing stimulus-response incompatabilities will increase age effects. Figure 26 shows the increased age effect obtained by Stern, Oster, and Newport (1980) when they changed a task from being either a simple response to a compatible binary choice task, and then to an incompatible binary choice task. Figure 27 shows a similar result obtained by Kay (1954) using a complicated twelve choice reaction time task. In each case the more complicated response calculation produced a much greater age effect. Why this would be so is not clear. Presumably the incompatability complicates the mental computations involved in the response selection process. While this is of interest theoretically, the practical importance of the phenomenon is probably slight, as good human engineering practice dictates the use of compatible stimulus-response mappings.

When does the age-related slowing in response selection begin to appear? Some reviews indicate that the effect only begins to appear in the 50s and beyond. This statement is apparently based upon the fact that statistically reliable changes in performance with age often do not appear until until late middle age. On the other hand, it is generally the case that people of age 30 are slightly slower than those of age 20, people in their 40s are slightly slower than those in their 30s, and so forth. This pattern suggests that the data might more accurately be described by assuming that there was a continuous slowing of response selection with age. To answer this question, we have calculated the fit of the linear regression equation

(5) Reaction time = A + B x (age)

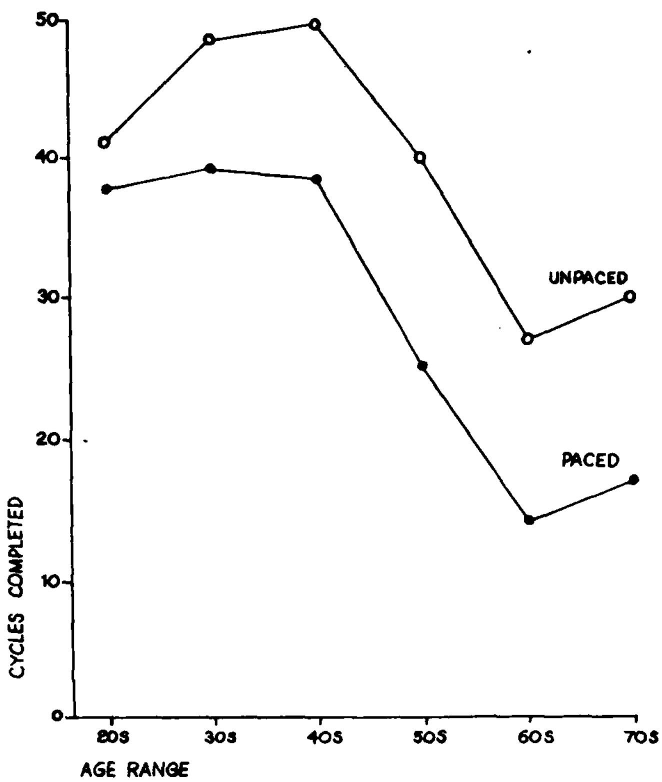


Figure 25. Number of cycles completed in a tapping task under paced and unpaced conditions. (Welford, 1977).

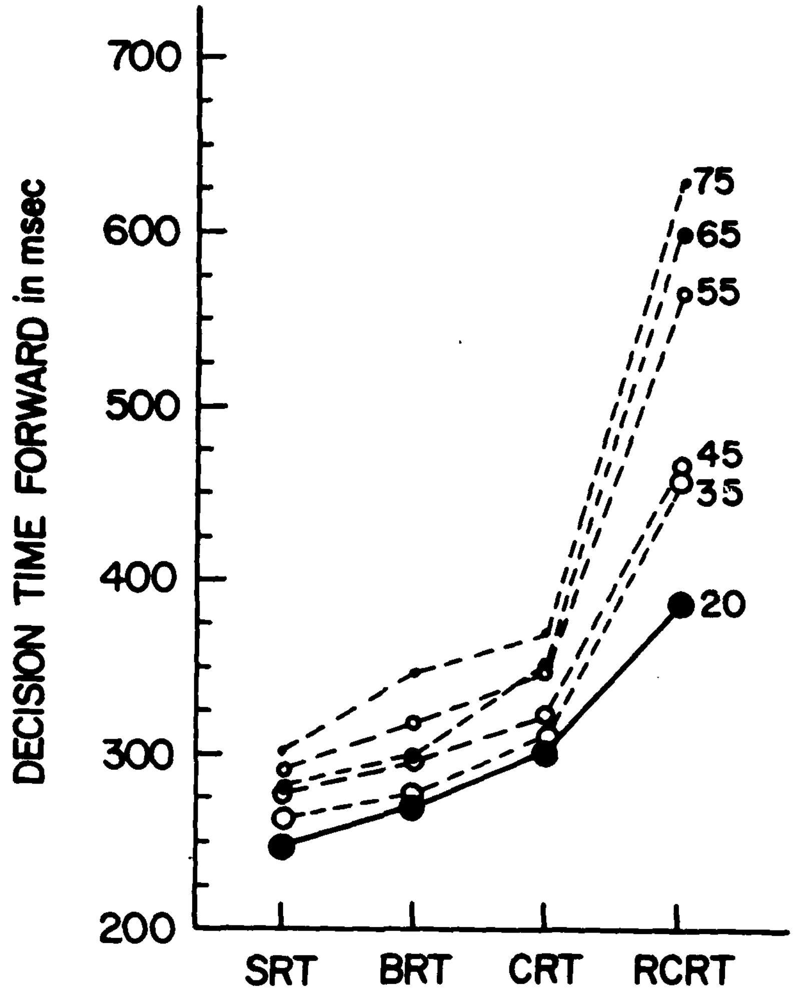
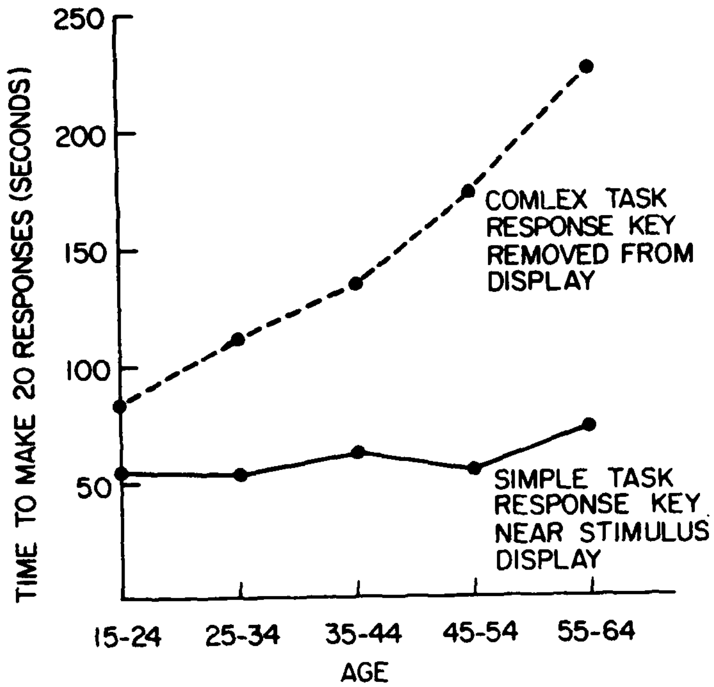


Figure 26. Change in reaction time as a function of age and type of task - simple reaction time (SRT), 'two handed task' reaction time (BRT), choice reaction time (CRT) and choice reaction time with incompatible stimulus-response pairing (RCRT). After Stern et. al., 1980).



TIME TO RESPOND TO SIGNAL AS A FUNCTION
OF AGE AND STIMULUS - RESPONSE COMPATABILITY
(KAY, 1954)

Figure 27.

Table 2

TASK	A	B	R^2
Speed of Writing (Birren and Botwinick, 1951) - Minutes	1.36	.02	.94
Two Choice Reaction Time. (Goldfarb, 1941) - Milliseconds	347	4.20	.78

Fit of Equation $RT = A + B\ (Age)$

For two simple tasks

Abbreviations: A - intercept

B - slope

to two widely cited data sets. To avoid spurious fits due to extreme deterioration of functioning in old age, we considered only the age range 20-65. The results of our calculitions are shown in Table 2. The analysis strongly supports the contention that a slowing of response selection begins by age 30, and continues gradually throughout adult life.

7. SPEED OF COGNITIVE PROCESSES

This section discusses choice reaction time (CRT) paradigms in which reaction time is determined by cognitive "computations" rather than by response selection. To understand what is meant by this, consider a skeleton schedule of events for a CRT experiment:

(1) A warning signal is presented.

(2) Stimulus information is presented

(3) Based upon an evaluation of the information, the subject selects and makes a response.

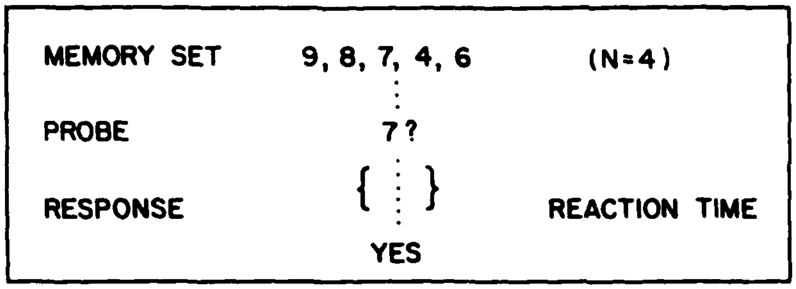
In the CRT experiments discussed in the preceding section, the evaluation component was minimized, because identification of the stimulus was equivalent to response selection. The studies described were rather like studying the time required to decide to brake upon seeing a red light. It is easy to arrange an experiment in which the evaluation phase is far from trivial. To repeat an example given earlier, one could instruct a subject to throw a switch to the right at step (3) if a prime number was displayed in step (2). Following the lead of a number of theorists (e.g., Baddeley, 1976), we shall describe the evaluation phase as requiring cognitive computations upon an internal representation of the external world. Most of these computatiions are assumed to take place in "working memory", which is thought of as a sort of workbench that holds information about the current state of external affairs. Working memory, however, appears to be limited in size, so that information must be continuously passed over from working memory into secondary memory for more permanent storage. Colloquially, one can grasp this distinction by imagining that you are listening to a speech. Working memory would contain a close to verbatim record of the exact words the speaker just uttered, while secondary memory would contain a representation of the ideas the speaker was trying to develop. It is assumed that during comprehension all computations take place in working memory, but that from time to time it is necessary to fetch information from secondary to working memory. Maintainence of information in working memory is held to be an active process, requiring attentional resources, while maintainence (but not the fetching) of information in secondary memory is thought of as a passive process. There is evidence that working memory and secondary memory depend on different physical processes. Discussing the evidence would carry us beyond the scope of this report.

One cannot speak of the effeciency of working memory computations, in general, because there are probably several different types of computations, each of which may respond to different variables. We shall review evidence concerning the interaction of age with four different types of memory computations; locating a verbal item in memory, comprehending and reacting to simple sentences, fetching semantic information into working memory, and the manipulation of visual-spatial images "inside the head." The first three computations are considered elementary steps in verbal thinking, while the fourth represents a non-verbal computation.

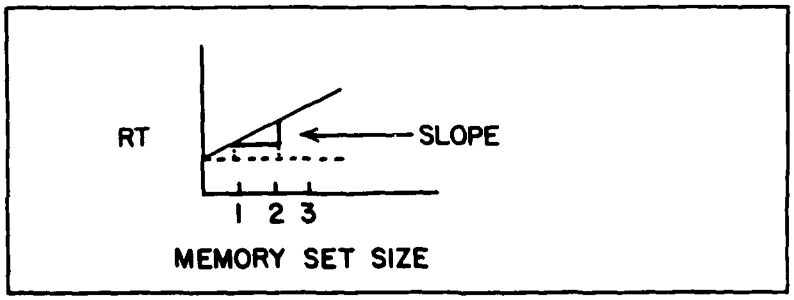
MEMORY SCANNING

It is generally agreed that one of the things that working memory does is to hold an (auditory?) representation of linguistic terms. Consider the example of listening to a speech, as described above. An extremely simple "verbal" task is to scan memory to determine whether or not a particular item is in the set. The speed of scanning working memory is usually tested by using a "memory scanning" paradigm originally developed by Sternberg (1966). Sternberg's procedure is shown in Figure 28. The subject is first shown a number (N) of familiar stimuli, called the "memory set". N is chosen to be small enough (usually 6 or less) so that the labels can be held in working memory. Once the memory set has been shown, a probe stimulus is displayed. The observer's task is to indicate whether the probe item was a member of the memory set. This can only be done by comparing the stimulus characteristics of the probe item to those in the memory set. Reaction time (RT) is typically found to be a linear function of the size of the memory set. The slope of this function can be regarded as an indication of the efficiency of the memory scanning.

A memory scanning experiment by Anders, Fozard, and Lillyquist (1972) is frequently cited as evidence that working memory is scanned more slowly with advancing age. Three groups of subjects were studied, with mean ages of 20, 38, and 68. The slope of the RT-memory set function was 39 msec/item in the youngest group, 63 in the middle aged group, and 71 in the oldest group. There was no difference in intercepts between the 20 and 38 year old groups. The intercept of the oldest group was



(a)



(b)

Figure 28. A sequence of events in memory scanning task. The slope is a measure of speed of access to information in working memory.

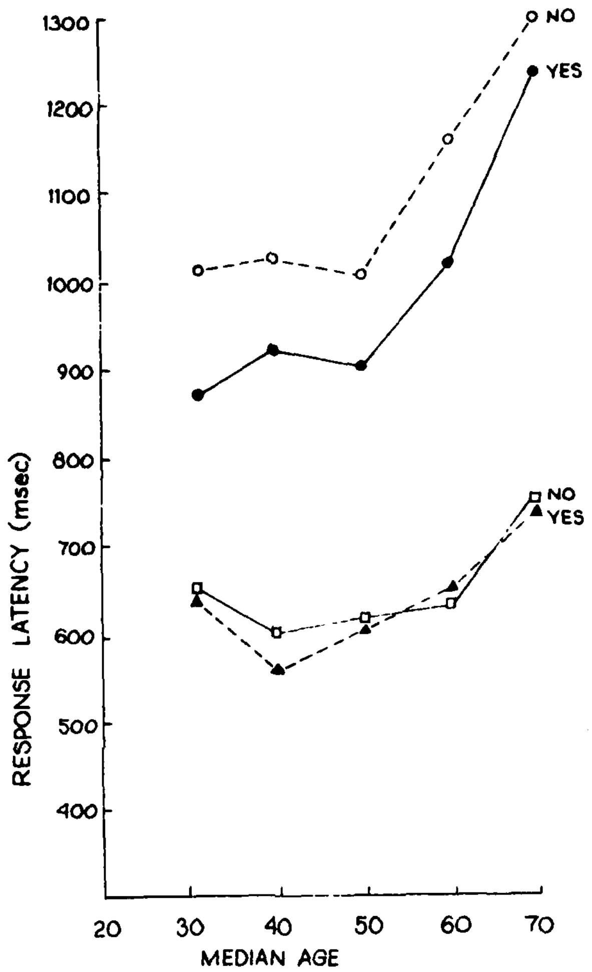


Figure 29. Time required to identify a character as a member of a designated set of "positive" items. Lower curves - items from front of alphabet. Upper curves - items from center of alphabet. After Thomas, et. al., 1977.

markedly higher than that of the two younger ones. A subsequent study by Anders and Fozard (1973) replicated this result for the young and old groups only.

Because this experiment is widely cited (e.g. Craik, 1977; Sternberg, 1975) critical examinations of both the data and the design are in order. A surprising finding was that the middle group, 36 year olds, performed more like the older than the younger group, even though the chronological age of the middle group was closer to the younger. Taken at its face value, this suggests that the speed of scanning working memory is an unusually age-sensitive function. However there may have been population differences other than age. The younger group was recruited from hospital staff members, while the two older groups were recruited from a panel of volunteers participating in a Veteran's Administration study of aging. It would be advisable to replicate this study, using either a longitudinal study or a cross-sectional study in which all subjects were recruited from comparable sources. It should be noted, though, that the old vs. young contrast is not in question, as the finding that the elderly have slow memory scanning rates has been replicated. The form of the age-performance function is still unclear.

A study by Thomas, Waugh, and Fozard (1978), using a related paradigm, suggests that the speed of memory scanning does decrease with age, but not as rapidly as the Anders et al. results would indicate. In the Thomas et al. study memory set size was held constant, by always using either six letters drawn from the front of the alphabet (a,b,c,d,e,f) or six letters from later in the alphabet, (p,g,k,t,r,l). A single letter was displayed on each trial. The task was to indicate whether or not the letter was a member of the memory set. Thomas et al. observed that, for some unknown reason, people are faster in responding if the memory set is drawn from the first part of the alphabet than from latter part. Regardless of why this is so, Thomas et al. argued that the fact itself indicates that more processing is required to match the letters in the second set. If computations in working memory generally slow with age, then age effects should be magnified when the "slow" set of letters is used. Some relevant portions of their data are displayed in Figure 29. The hypothesis was clearly supported. Furthermore, the relation between reaction time and age was either linear or positively accelerated. This contrasts with the negatively accelerated function obtained by Anders et al.

The logic of memory scanning experiments can be extended to studies of retrieval of information from secondary memory. The most straightforward way to do this is to extend the size of the memory set. A great deal of research (conducted outside of the study of aging) has shown that working memory contains at most about nine items. In order to test secondary memory, one simply uses a memory set containing more than ten items, thus ensuring that at least some of the list is retrieved from secondary memory. Anders and Fozard (1973) did this, and found even stronger age effects on scanning information in secondary than in primary memory. Unfortunately for our purposes, Anders and Fozard only tested young (20s) and old (65+) subjects.

Sternberg's memory scanning paradigm is questionable as a way of testing the scanning of secondary memory, because of the difficulty of ensuring that a particular item is retrieved from secondary memory, and because there is considerable doubt as to whether the linear relation between RT and list size holds for lists too long to be held in working memory. Since the question of age effects on speed of access to information in secondary memory remains a sensible one, somewhat different paradigms have been developed to address it. Fozard and Poon (1978) had people learn twelve pairs of arbitrary word-word associates. Hypothetical example of the items used are:

dollar -- igloo
page -- table
foot -- mouse .

Each item was presented twice in a block of twenty four trials, and blocks were repeated until learning was complete. After the first block learning was by the anticipation method. A stimulus item would be presented (e.g. dollar..?), a response recorded, and, if necessary, corrected. Using this design, one can examine the time required to make a response on the second presentation in each block as a function of the interval between the first and second presentation. The argument for doing so is that if two trials using the same item follow each other immediately, the answer will be fetched from primary memory, whereas if several other trials intervene the response must be fetched from secondary memory (Atkinson and Shiffrin, 1968). At short intervals there was only a slight difference in reaction times between three age groups (mean ages 20, 53, 63), while at longer inter-trial intervals the two older groups were markedly slower.

The primary-secondary memory distinction was expanded upon in an experiment by Waugh, Thomas, and Fozard (1976) which permitted a direct comparison of retrieval times from each type of memory. In the first part of this experiment, subjects simply read printed words. There was virtually no difference in naming time across a wide age range. In the second part of the experiment, 12 item paired-associate lists were presented with a procedure similar to that of the Fozard and Poon study. Following the presentation of set of pairs, the cue term for the last pair would be presented. An abbreviation of the sequence would be:

yam - zoo
vat - wig
ink - jam

Table 3

Task	Age 37	50	58
Word Naming	584	583	589
Paired Associates, Working Memory	721	741	795
Paired Associates, Secondary Memory	1222	1469	1732

Geometric Means (msec) of Reaction Time for naming words, and retrieval of paired associates from working memory and secondary memory (Waugh et al., 1978).

eel - fox

eel - ?

The time required to produce the response ("fox" for the "eel" cue) was recorded. Presumably the retrieval of the response term was from primary memory, since no items intervened between presentation and test. Hence RT was taken as a measure of the speed of primary memory retrieval.

In the second part of the experiment, participants memorized all twelve pairs of associates. Mnemonic cues were given to aid them in doing this. After the list of associates had been memorized, individual cue words were presented, and the responses to them were timed. In this case the presumption was that retrieval was from secondary memory. Table 3 shows the results. A positively accelerated function relating RT to aging is clearly evident in the retrieval data. Retrieval from secondary memory is considerably slower, and the age effects are larger.

Further confirmation of the hypothesis that aging has a substantial effect on retrieval time from secondary memory was obtained by Poon and Fozard (1980), using a continuous recognition task. In this experiment subjects were presented a long series of words. With each presentation they had to indicate whether the word had been presented before. 20, 50 and 60 year olds showed small, but reliable RT differences for words that were still in the span of primary (working) memory. The differences in retrieval times became much larger when the words had to be retrieved from secondary memory.

The literature seems strong enough to warrant a firm conclusion. In situations in which an individual is queried about information that has been received within the last few minutes, information retrieval becomes slower as we age. Effects are clearly evident by age 50. The data is sparse for the 20-50 age range, but presumably there is some slowing of response. The amount of slowing and the effect of age upon slowing of information retrieval will be greater if the information must be retrieved from secondary rather than working memory. While the practical importance of these observations has not been demonstrated (or even investigated), the fact of slowing should be kept in mind in the design of work situations where a person must keep track of rapidly changing situations. Given the experimental evidence, studies of age effects on tasks such as those of a dispatcher, air traffic controller, or fire direction officer seem warranted.

FETCHING INFORMATION FROM SEMANTIC MEMORY

The items of information in working memory are not transductions of the physical stimulus, they are interpretations of that stimulus. Very many experiments, which we shall make no attempt to review, have shown that when a person is shown a meaningful symbol, such as the visual stimulus CAT, the entry in working memory is not a representation of lines and angles, but rather a representation that includes the semantic meaning of our word for "small, furry domestic feline." Obviously this semantic information must be retrieved from permanent memory in order to understand speech. Rapid access to semantic information is important in many non-verbal problem solving situations as well, although this may be because humans can use verbal representations of these problems. Because access to semantic information is such an important feature of our thought, it is reasonable to ask whether or not the speed of access to semantic information changes with age.

There are actually three questions here; how is semantic access to be measured, is it a reliable dimension of individual variation, and does this dimension of variation correlate with age? Several procedures for measuring semantic access have been developed. They all require that a person calculate a response by retrieving some well known fact. One example is a simple word recognition task called "lexical identification". People are shown either a common word or a non-word letter string that is formed according to the rules of English orthography. An example of a non-word would be RADE, which is not a word, but does not violate any spelling or pronunciation rules. Slightly more complex tasks force people to compare the semantic meaning of two or more words, as in responding to the question "Is a canary a bird?" Tests of semantic access are not always based on written language. An observer can be asked to name a highly familiar visual stimulus, such as a picture of a bird or a house. The common feature of all these tests is that they require the calculation of a response based upon knowledge of semantic information about the world, rather than upon knowlege about a particular episode in a person's own past history (Tulving, 1972).

It does not seem to matter too much which of these procedures is used to measure a person's speed of semantic access, as the resulting measures are highly correlated across individuals (Hunt, Davidson, and Lansman, 1981; Palmer, MacLeod, Hunt, and Davidson, Note 2.) The fact that there is a reliable "semantic access" dimension of individual differences appears to be clearly established.

Age effects have been little studied, which is unfortunate given the importance of semantic access in everyday reasoning. The only adequately controlled studies that we located were related experiments by by Thomas, Fozard, and Waugh (1977) and by Eysenck (1975). The Thomas et al. study is of more interest here because it covered the age ranges 30-60, whereas Eysenck considered only groups in their 20s and late 50s. People were asked either (a) to name pictures of common items or (b) when given a name, to tell whether the following picture was an example of the name (as in the word "dice" followed by a picture of dice).

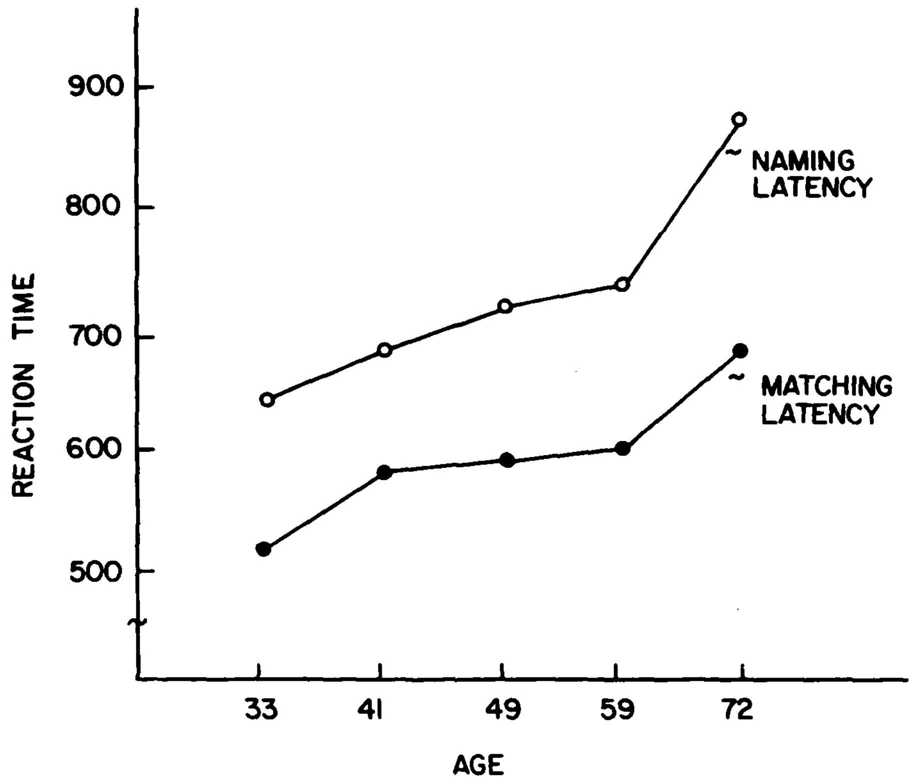


Figure 30. Time required to name an item or match it to an indicated semantic category. After Thomas et. al., 1975.

Thomas et al.'s data is displayed in Figure 30. Age effects are evident.

We would hesitate to generalize widely from the Thomas et al. study to semantic access in general. Although picture identification and other strictly verbal measures of semantic access are highly correlated in young adults (Hogaboam and Pellegrino, 1978; Hunt et al., 1981) this may not be the case for people in their 40s and 50s. A picture naming task has obvious visual as well as verbal components. The psychometric data clearly indicates that age affects visualization adversely, while verbal capacities are retained. It should be noted that measures of semantic access are intentionally designed to be tests of the "availability" of culturally relevant information. As such, they epitomize Horn and Cattell's definition of the crystallized (Gc) intelligence, which is said to increase with age. It is difficulty to know what sort of prediction to make concerning performance in a speeded semantic task that pits an expected increase in crystallized intelligence against an expected decrease in cognitive computation. Depending on which of the two age-related processes dominated, one could make a case for predicting an increase or decrease in speed of semantic access at a particular age. Clearly the question can only be answered by research that explores the performance-age function in detail, for a variety of semantic access tasks.

MANIPULATING VISUAL IMAGES IN THE HEAD

The last paradigm to be discussed differs from the others in that it requires the manipulation of a visual "mental image" instead of the manipulation of language information. Based on the psychometric findings, it is known the ability to make that such manipulations does not reflect the same dimension of individual differences as does the ability to do verbal tasks.

Experiments that seek to determine the speed with which a person manipulates visual information are usually based upon a variation of the "spatial rotations" paradigm developed originally by Shepard and Metzler (1971). The task is illustrated in Figure 31. Two meaningless figures are presented, at different angles of orientation with respect to the observer's line of sight. The observer must indicate whether or not the two figures are identical or are mirror images of each other. This task is of interest because it can be thought of as an experimental analog of tasks that require a person to reconcile different visual perspectives, a skill required in a number of mechanical operations. RT in spatial rotation experiments can be described by the equation

$$(6) \qquad RT = A + BO,$$

where θ is the angle of rotation required to bring the two figures into spatially congruent mental representations. The parameter B can be regarded as the time required to "rotate" a mental image through one degree (Shepard and Metzler, 1971; Cooper and Shepard, 1973).

Gaylord and Marsh (1975) found age differences in the speed of mental rotation, as measured by the B parameter. However, they only contrasted young adults with elderly (65+) individuals. Berg, Hertzog, and Hunt (1981) obtained mental rotation data from university alumni (hence, a "superior ability" group) ranging in age from 20 to 60. In this study the subjects practiced the task for four days, to lessen the criticism that older subjects perform more slowly because of a lack of familiarity with this type of task. The results are shown in Figure 32. RT increased steadily with age and with the angle of rotation. In addition, there was an interaction between age and the angle of rotation, indicating age differences in the speed of rotation itself (the B parameter). Table 4 shows Berg et al.'s data for the A and B parameters as a function of age. The data show a progressive increase in both parameters with increasing age. This is consistent with the hypothesis that the speed of computation upon a visual, primary memory representation increases with a person's age. Since visual image manipulation and reasoning is sometimes said to be important in a variety of mechanical and motor control tasks, it would be of interest to investigate further the relationship between age, spatial-visual image manipulation, and performance in selected occupation. It would be particularly interesting to determine whether the age effects that are so clear in Berg et al.'s data hold for individuals who practice spatial tasks in their daily lives, such as aviators, professional automobile drivers, and architects.

THE CONTINUITY OF AGE TRENDS IN MENTAL COMPUTATION.

The literature on mental computation is remarkably consistent. There appears to be a substantial slowing in the speed of mental tasks as one passes through the working years. In general, the greater the complexity of the mental computation, the greater the amount of slowing observed in the early 60s and beyond (Cerella, Poon, and Williams, 1980). In the section on response selection we noted that there is a linear relation between chronological age between 20 and 60 and the time required to select responses. Does a similar relation hold for the time required by more complex mental calculations? Table 5 shows the results of fitting a linear function to data from several of the experiments that have been cited in this section. In summarizing the data on motor movement time, we observed that many aging effects upon RT relations can be summarized by the linear regression equation of Equation (5). How well does this fit the

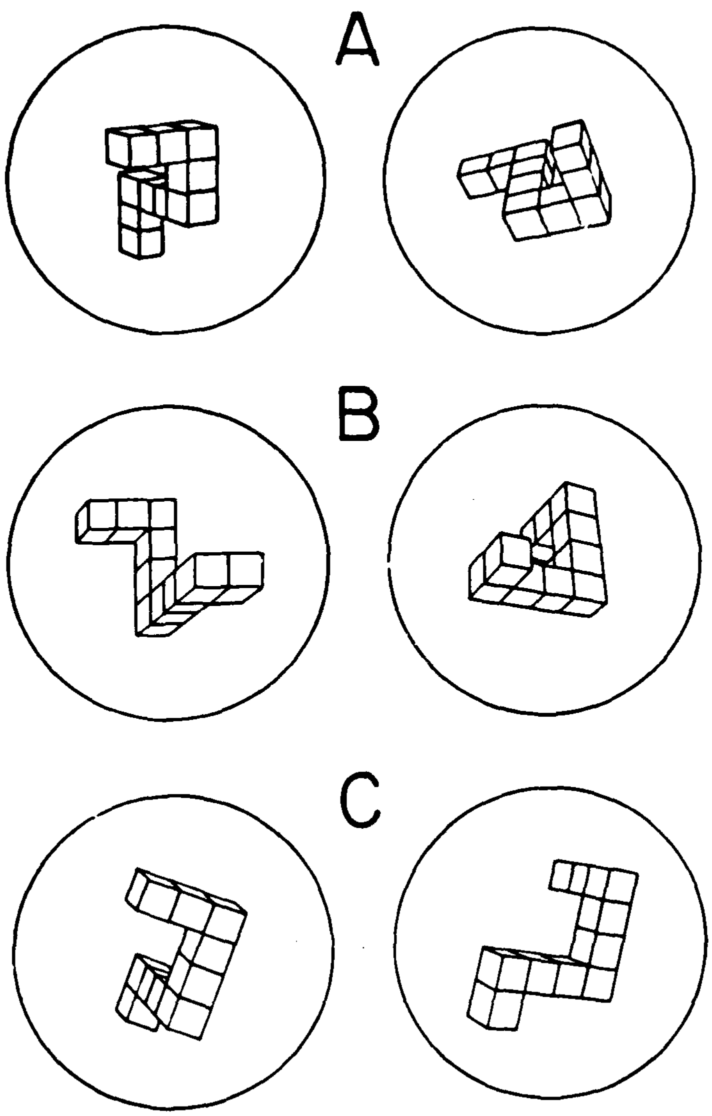


Figure 31. A visual rotation task. Is the figure on the right identical to the one on the left except for orientation?

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AGE RELATED CHANGES IN COGNITION DURING THE WORKING YEARS.(U)
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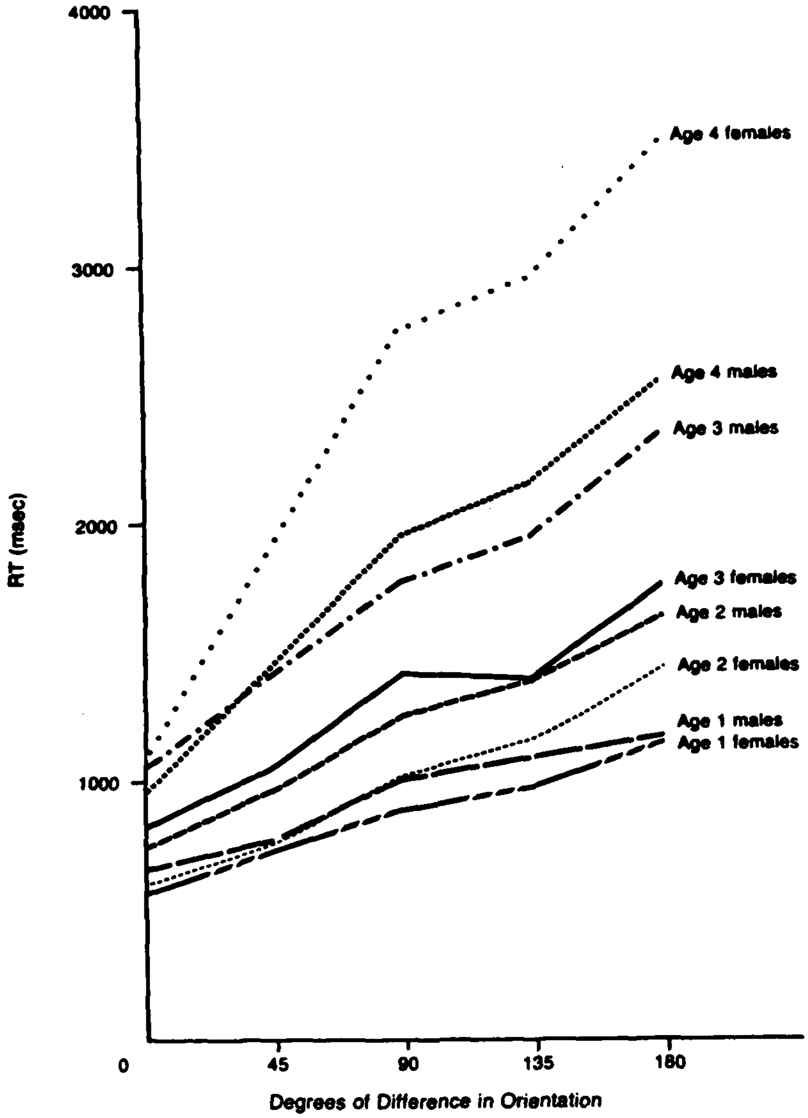

Figure 32. Reaction time to identify geometric figures as "same" or "different" as a function of angle of rotation, age, and sex. Ages 1-under 25, 2- 25-35, 3- 35-45, 4- 50+. (Berg, Hertzog, and Hunt, 1981)

Table 4

Slopes, and Intercepts for
Age Groups over Days of Practice

Mean Age	Sex		Day 1	Day 2	Day 3	Day 4
21	Females	Slope	6.65	4.69	3.63	3.26
		Intercept	910.40	683.30	606.10	580.40
21	Males	Slope	7.79	4.90	3.88	3.59
		Intercept	1009.80	744.00	679.40	648.60
32	Females	Slope	9.66	6.66	5.83	4.70
		Intercept	891.40	731.00	636.10	574.80
33	Males	Slope	7.30	5.72	5.38	4.77
		Intercept	1046.70	838.70	758.10	762.30
49	Females	Slope	8.87	7.73	6.67	5.84
		Intercept	1176.50	921.50	856.20	794.30
53	Males	Slope	10.43	9.42	9.28	7.60
		Intercept	1412.60	1124.80	997.60	1057.70
62	Females	Slope	17.96	17.00	14.36	13.17
		Intercept	2145.80	1463.80	1446.60	1167.70
64	Males	Slope	10.40	9.89	9.32	8.92
		Intercept	1337.70	1224.90	1042.20	1117.30

Data from Berg, Hertzog, & Hunt, 1981.

Table 5

Task	A	B	R^2
Primary Memory Retrieval, Familiar Stimulus (Thomas et al., 1977)	527	1.84	.27
(Reduced case of Thomas et al. data)	357	5.00	.99
Naming items (Thomas et al., 1978)	439	5.76	.93
Matching semantic categories (Thomas et al., 1978)	412	3.57	.91
Response to tone while doing a Hard Verbal Memory Task (Hunt and Lansman, 1981)	178	3.66	.93

Fit of the equation $RT = A + B\,(Age)$ to data from complex reaction time tasks: All data is milliseconds.

data for tasks that depend more upon complex memory computations? The fits are not as good as were obtained for the simpler tasks, but are still substantial. The major exceptions are that 1) in Thomas et al.'s (1977) "semantic" studies, age effects were negatively accelerated functions of absolute age, and 2) that in each of the conditions of Thomas et al.'s (1978) primary memory study there was one group whose results were not in the order predicted by Equation 5. In particular, the 30 year old group was unusually slow in dealing with "familiar" items. When these groups are removed from the analysis (the "reduced" case of the Thomas et al. data) the fit of the equation is substantially improved.

The case for the proposition that mental activity slows continuously with age seems strong.

8. ACCURACY OF INFORMATION RETRIEVAL

The discussion will now shift from a review of studies of speed of responding to studies of accuracy. The material reviewed in this section deals with age related changes in the retrieval of information from memory. Section 8 deals with changes in problem solving and reasoning, tasks that require people to consider the consequences of explicitly presented information. Section 9 critiques knowledge of the relation between age and accuracy of mental processes.

AGE CHANGES IN WORKING MEMORY

How many pieces of information can a person keep in mind at once? In a memory span experiment, a person is asked to recite a small amount of information presented seconds before testing. The Digit Span subtest of the Wechsler Adult Intelligence Scale (WAIS) is a good example. The examiner reads a list of digits aloud, and the examinee is asked to repeat them, either forwards or backwards. The number of items correctly recalled is called the digit span. Estimates of word and letter span usually do not differ greatly from digit span. Because of this, Miller (1956) has suggested that the unit of memory is the meaningful symbol, which he refers to as a "chunk", rather than the mathematical measure of information in that symbol. Based on a survey of the literature, Miller (1956) proposed the "magic number seven, plus or minus two" as a reasonable estimate of the number of chunks that could be held in working memory. This is perhaps a bit optimistic. Miller's data was drawn mostly from studies of university students. Studies of more general populations indicate that adult digit span is usually from four to seven (Matarazzo, 1972; Talland, 1968). Values below this range are considered indicative of brain damage. Values above this probably indicate that the person being tested has developed some special trick for memorizing lists (Matarazzo, 1972; Chase, Lyon, and Ericsson, 1981). Providing that digit (or letter, or word) span is tested in a quiet area, estimates of its value decline only slightly over the adult years (Craik, 1968, 1977). Individual variation within an age group appears to be far greater than variation due to age.

What produces a limit on memory span? Several hypotheses have been proposed. All are based upon the assumption that the memorizer sees the object, names it, and then holds an (internally generated) name in working memory. After an extensive review, Dempster (1981) concluded that the limiting factor in span is normally the speed with which an individual can recall the name of an external stimulus. This fits well with the observation that age differences in digit span are small, for Waugh et al. (1978) report only minimal age differences in naming latencies.

Working memory should not be thought of as a set of slots, analagous to post office boxes. It is more likely that working memory consists of a set of records that are kept in a high state of arousal (loosely, "rehearsed") by an active process of attending. How does one remember a list of items? By rehearsing verbal labels inside the head. If rehearsal is interrupted, memory span drops drastically. To illustrate, memory span drops to almost zero, over as short a period as 18 seconds, if the examinee is asked to count backwards by threes during the period between list presentation and recall (Peterson and Peterson, 1959).

Holding information in working memory is an attention demanding task. Applying Kahneman's (1973) mental resource model of attention, whenever a mental task requires temporary retention of information in working memory, attentional resources must be diverted from other ongoing mental activities. Conversely, the presence of other ongoing mental activities will limit the amount of attentional resources that can be allocated to the memory task. There is a good deal of experimental support for this proposition. In general, it is difficult to hold items in memory while other problem solving is going on, and the act of problem solving will reduce the memory span. For instance, the time required to comprehend a simple sentence is increased if people are asked to hold irrelevant information (e.g. a set of digits) in working memory as the sentence is being presented (Hitch, 1980; Lansman, Note 9). Mathematics problems that place demands on working memory, such as additions with carries, are harder than similar problems that do not place a burden on working memory (Hitch, 1978). The logic used to explain these phenomena is essentially the same as that used to explain interference in dual tasks. It is asserted that in some situations a person must conduct two sorts of mental computations at the same time; rehearsal of information in working memory and "something else." The two tasks compete for limited attentional resources, hence performance on

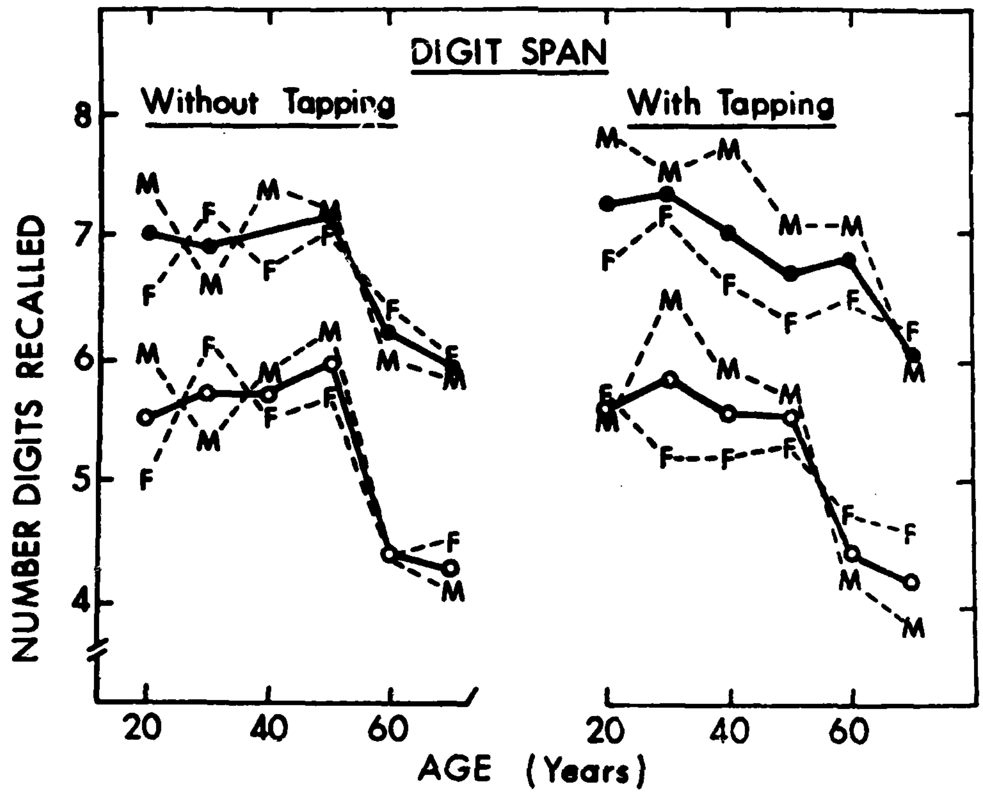

Figure 33. Memory span for digits, with and without ancillary tapping task. Data is shown as a function of sex and age (Botwinik and Storandt, 1974).

one or both tasks should deteriorate.

If the attention competition explanation is combined with the attentional deficit hypothesis that attentional capacity decreases with age, it follows that age-related decrements in measures of working memory capacity should appear in situations in which other ongoing mental activity impose demands upon attention -- i.e., a dual task paradigm. While literature reviews have suggested that the predicted age effect does occur, examination of the primary literature indicates that the effects are small and only appear after age 60. Figure 33 shows some data gathered by Botwinick and Storandt (1974), in which digit span forward and backward was calculated in the normal manner and while subjects were doing a concurrent finger tapping task. There was virtually no change in digit span before age 60, in either in single or dual task conditions. Similar results have been reported by Talland (1965) using slightly different dual tasks. The expected age x task condition interaction appeared, but only after age 50.

Memory span tasks are usually self paced. The attentional demands of a memory task can be increased by using an experimenter-paced situation in which the contents of working memory must be continually updated and tested. Active use of working memory in this way seems to be an important element in many occupational tasks. An air traffic controller, for instance, must keep track of a changing traffic situation. This situation was mimicked in an experiment conducted by Hunt and Lansman (1981) for somewhat different purposes. We earlier presented data on the response selection aspects of their study. Here we report a second additional analysis, in which we look at age effects on recall from working memory as a function of age. The conditions that are relevent are their single task conditions, in which subjects had to keep track of the current state of a continuously changing set of letter-digit pairs. For example, in a typical sequence the following events would occur:

Event on screen	Response
A = 5	
B = 2	
A = ?	5
A = 7	
B = ?	2
B = 6	
etc.	

The example given is trivial, because there are only two variables to be recalled, the numbers currently paired with A and B. The task is much harder if five or seven variables are to be used. Performance on this task has been shown to depend heavily upon working memory (Atkinson and Shiffrin, 1968). Figure 34 shows accuracy of performance plotted as a function of age and complexity of the task (2 variables opposed to 5). There is a a slight decline in performance with age, primarily due to reduced performance of people beyond 40.

SECONDARY MEMORY

Information must be recalled from secondary memory if information presented exceeds the capacity of working memory, or if some activity requiring working memory intervenes between the time that information is presented and the time that it is to be recalled. Examples would be recalling a list of twenty to thirty words, or recalling a five word list, after having done arithmetic in the period between list presentation and recall.

The easiest way to test secondary memory is to extend the memory span experiment by presenting a list longer than can be held in working memory. The assumption is that this forces the recall of some items from secondary memory. Figure 35 presents data on the accuracy of recall of lists of words as a joint function of list length and age (Talland, 1968). Age effects do appear, but they are small.

An alternative technique for studying recall from secondary memory utilizesa phenomenon known as the serial position effect. It has long been known that if a person attempts to recall items from a list that exceeds memory span, the best recalled items are those at the last of the list ("recency"--the items most recently presented are recalled best), followed by the items at the front of the list ("primacy"), and then by the items in the middle. The usual explanation for the recency phenomenon is that items later in the list force the earlier items out of working memory. If recall is tested immediately after the list is presented, the last few items will be resident in working memory, while the remaining items must be recalled from secondary memory. Craik (1977) has reported data showing that there are no age effects on recall of items in the recency portion of a list, but that age effects do appear in recall of items from the earlier parts of a list. The lack of an age by recency interaction is consistent with the finding that the capacity of working memory does not change with age, but that the effectiveness of retrieval from secondary memory does.

A test of secondary memory simultaneously tests three things, the ability of a person to transfer information from primary to secondary memory during the storage stage, the ability to retain information in secondary memory for some period of time, and the

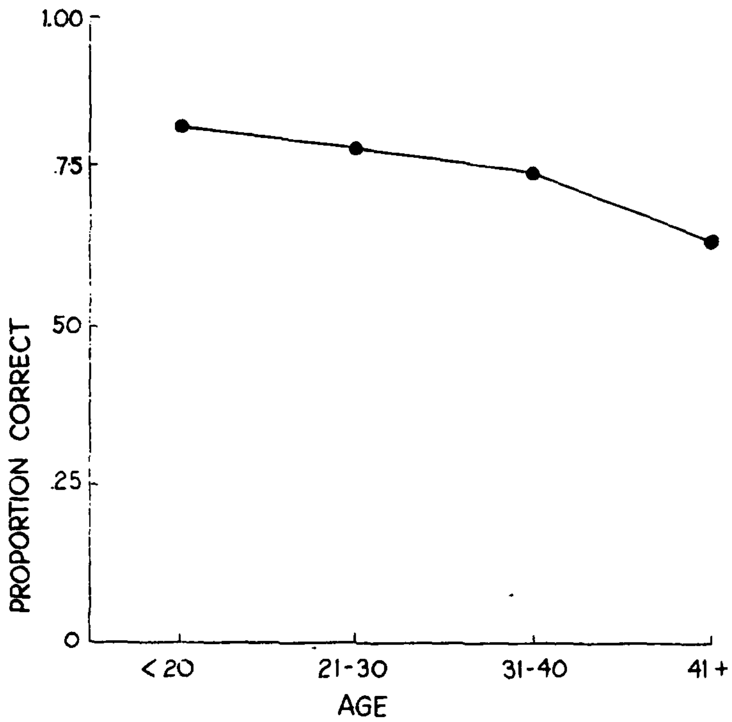

Figure 34. Accuracy of recall is continuous in paired associates task - hard condition. Hunt and Lansman, 1981.

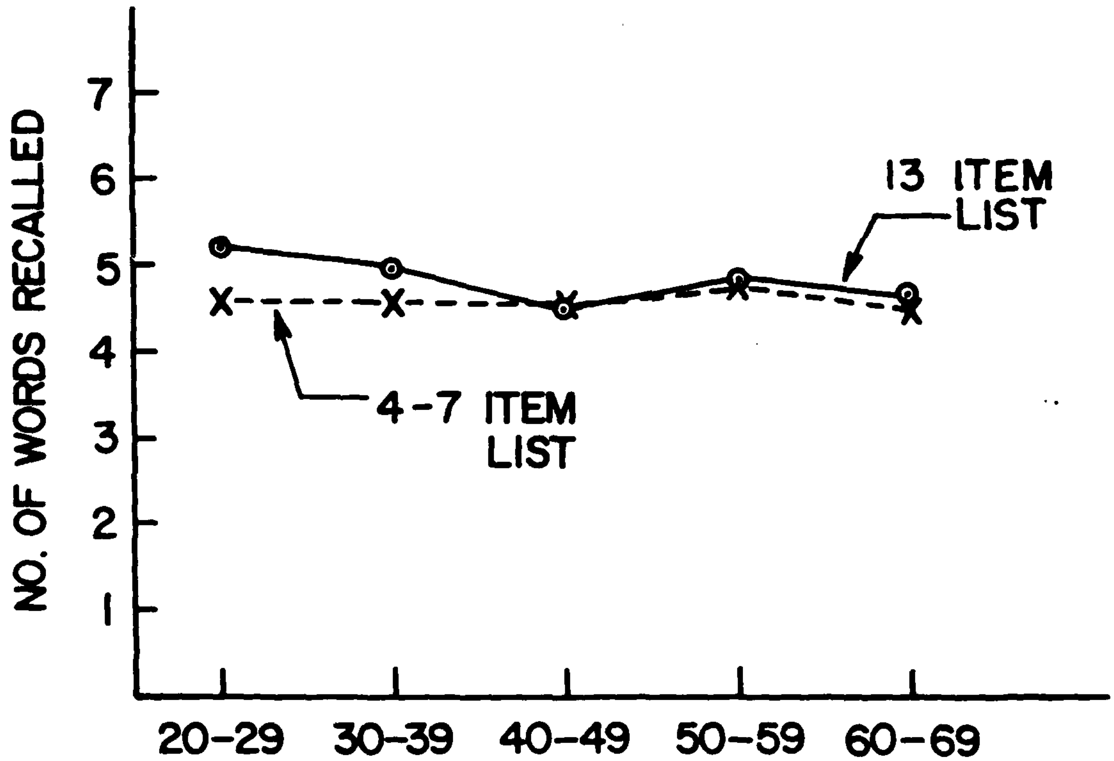

Figure 35. Number of words recalled immediately as a function of list length. (After Talland, 1968).

ability to retrieve that information given whatever cues are presented when retrieval is required. Norman and Bobrow (1979) present a useful way of conceptualizing the three phases. During the storage phase a person establishes a "description" of the information to be stored. This is roughly analagous to a librarian's cataloguing a book when it is purchased. Certain facts about the information to be stored are noted, and these are used to establish a scheme of references that can be used for later retrieval. Imagine a person trying to memorize a list containing the word "cat". Part of the referencing scheme for this word might be based on properties of the word itself (e.g. "cat" sounds like "bat", "cat" is an animal) while other references might be derived from properties of the referent, or from idiosyncratic facts in a person's prior information structure (e.g., "My aunt Elaiva has a cat, think of her holding it"). Once the active cataloguing process has been completed the information itself is assumed to reside in memory, without requiring further (attention demanding) maintenance. When retrieval is required some cues will inevitably be present. These cues are used to determine a retrieval scheme analagous to the procedure a library user executes when trying to find information. If the retrieval scheme and the descriptions match, the information is recalled. Otherwise it is not. Successful memorization thus depends on two things: the development of schemes for description and retrieval, and the extent to which the two schemes match.

The development of storage and retrieval schemes fits into Schneider and Shiffrin's (1977) definition of attention demanding controlled processes. According to the attentional deficit hypothesis, memory should be vulnerable to age effects as the schemes are being constructed. The retention phase, being passive, should not be sensitive to age and its associated reduction in attentional capacity. Age effects on information retrieval should be found when the storage and retrieval phases require extensive computations in themselves, or when storage and retrieval occurs in competition with other cognitive computations. On the other hand, the effect of retention interval, per se, should not be influenced by age.

In an elegantly designed study, Wickelgren (1975) found precisely these results. He used a complex version of the continuous recognition memory paradigm, in which a person is shown a series of items, some of which are presented two or more times. The person's task is to respond to indicate when an item presentation is repeated. By applying a fairly complex mathematical analysis to the data, Wickelgren concluded that there were age effects in storage and retrieval, but not in retention. Unfortunately for our purposes, Wickelgren only contrasted the performance of children, young adults, and the elderly. Wickelgren's experiment should be replicated on adults in the middle age range. The fact that young and old adults were equivalent in retention implies that retention is stable in middle age as well. On the other hand, without testing people in the

20-60 age range, we have no way of tracing the change in storage and retrieval functioning over the working years.

Secondary memory can be tested by recall, which forces construction of a retrieval scheme; recognition, which minimizes the need to construct a scheme; or by cued recall, in which assistance is provided in constructing particular types of retrieval schemes. Table 6 shows the data from a much cited study by Schonfeld and Robertson (1966), in which people of varying ages were required either to recognize or recall arbitrary lists of 24 words. There were virtually no age differences in recognition. Recall dropped regularly with age over the 20 to 60 range. This data is typical of data obtained in several other studies contrasting recognition and recall performance. The result is obviously consistent with the attentional deficit hypothesis.

A further test of the interaction between memory performance, age, and attentional demands could be constructed by experiments that attempt to show exacerbated age effects in dual task situations, similar to the studies that have shown primary memory deficit in dual tasks. According to the hypothesis, a competing task should increase age-related drops in memory if it competes for attention during the storage or retrieval phases, but should have no effect if it is introduced during the retention phase. Such experiments would be of interest in themselves and because they seem to be analogous to real world situations; e.g. trying to memorize or recall something as you are distracted. We are unaware of any studies that have used such a paradigm.

The argument that establishing a description is important in memorization has been phrased in a somewhat different way by Craik and Lockhart (1972; Craik, 1979), who use the term "depth of processing". In the Norman and Bobrow terminology, Craik and Lockhart claim that in constructing descriptions there is a fixed order of elaboration upon the information presented, beginning with noticing physical features (e.g. "cat" has a particular visual shape), then any related physical codes ("cat" sounds like "bat"), and finally a network of semantic associations. Craik and Lockhart referred to the predicted ordering as representing progressively deeper processing, and asserted that deep processing had to be completed in order to ensure memory retrieval. The necessity for a fixed order of processing has been questioned. An elaborate description can be produced at a "shallow" level and still serve as a good description to guide retrieval (Baddeley, 1978; Nelson, 1977). According to Norman and Bobrow's analysis, the important variables are how much processing is done at storage time and how well the description matches the retrieval scheme, and not what type of processing is done. Regardless of the details of this debate, it does seem that Craik and Lockhart's distinction between shallow and deep processing may well represent the normal procedure used in establishing descriptions. Studies of mnemonists (Chase, Lyon, and Ericsson, 1981; Hunt and Love, 1972) have shown that very good memorizers do adopt schemes that

Table 6

Mean Recognition and Recall Scores by Age

Age Range	N	Recognition	Recall
20-29	36	20.01	13.78
30-39	23	19.48	12.30
40-49	32	19.53	10.01
50-59	21	19.90	9.57
60 +	22	20.09	7.50

Data from Schonfield and Robertson, 1966.

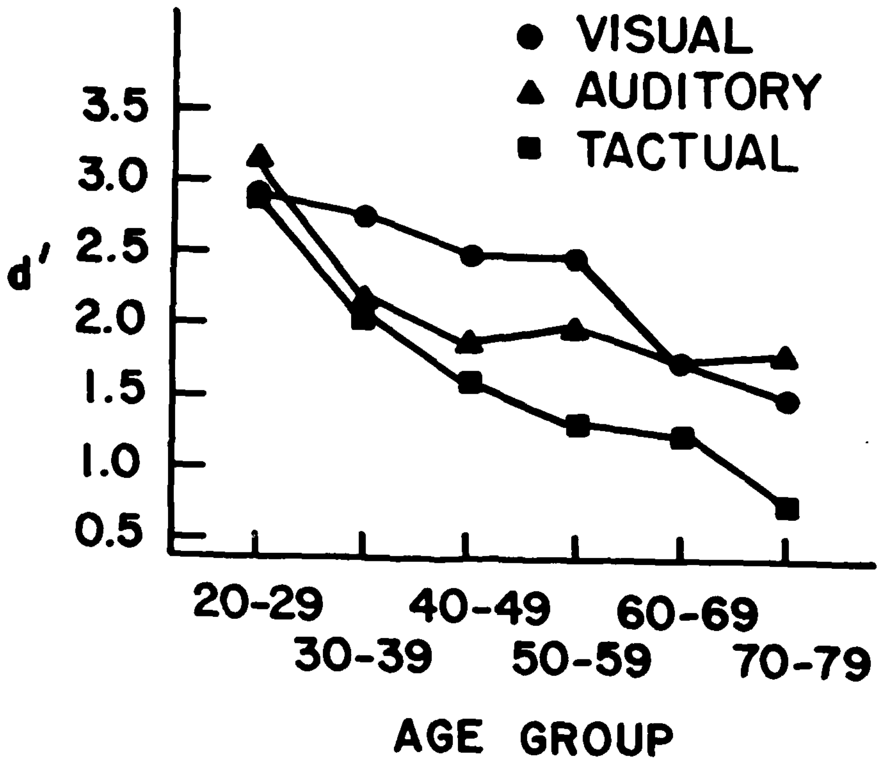

Figure 36. Recognition Memory (d' units) for auditory, visual, and tactile stimuli. (Riege and Inman, 1980).

emphasize deep processing.

The deep processing concept is another example of the use of an attention demanding controlled process to fix information in memory. If attention demanding processes are most affected by aging, it follows that age effects on memory should be most pronounced when deep processing is required. Simon (1979) tested this hypothesis by presenting supraspan lists of words for a fixed period of time. Retrieval was aided either by presenting an auditory cue (e.g. cueing "nog" by "smog") or a semantic cue (e.g. cueing "hog" by "pork.") The argument was that the phonetic cue, representing shallow processing, should be effective at all ages, but that the semantic cue, representing a level of processing reached only by fast processors, should be effective only for younger subjects. Older people (mean age 61) showed less recall than younger subjects (mean age 20) in all conditions but the differences were greatest for semantic cueing. Middle aged participants (mean age 43) showed intermediate results. Simon concluded that semantic processing was most affected by age, and that effects appear as early as age 40. This conclusion is similar to that reported by Eysenck (1974), in a study that showed semantic coding deficiencies in 50 year olds, compared to 20 year olds.

An alternative way to test the attentional deficit hypothesis is to look for the absence of age effects in situations in which there is no draw on attentional resources. It has been argued that some kinds of information can be stored and retrieved "automatically," i.e. without attentional resources being expended. Memory for the frequency with which events occur and memory for the temporal order of two events have been offered as examples of automatic memorization. Memory for both frequency (Hasher and Zacks, 1979) and temporal order (Perlmutter, Metzger, Nezworski, and Miller, 1981) has been shown to be equivalent in 20 year old and 60 year old subjects. It is hardly likely that there would be effects in the age ranges in between.

All the tasks that have been described so far depend upon verbal memory. Would the picture change if memory for visual events were tested? The question is not easy to answer, because our normal memory for visually presented events may depend in part upon the verbal processing that we do as we name the events. One study (Reige and Inman, 1981) has been reported of memory for "unlabellable" visual, auditory, and tactile stimuli. Recognition memory for all three types of information dropped with age. The results are shown in Figure 36. Note that the greatest drops in auditory and tactile memory appear relatively early in adulthood, while memory for visual stimuli did not drop until the 50s.

The delayed drop in visual memory may be questioned on the basis of the data from the Hunt and Lansman (1981) experiment. In one section of that study, they replaced the paired associates task with a visual pattern recognition task. There were two levels of difficulty involved, depending upon the number of elements in the visual pattern. Figure 37 shows that accuracy dropped as a function of age for both the easy and hard visual patterns. In contrast to the Riege and Inman results, the major age differences occurred between ages 35 and 46.

There appear to be age related drops in both storage and retrieval of information in secondary memory, but the age related changes are not large. The attentional deficit hypothesis serves as a rough guide for thinking about the age-related changes in performance, and *suggests* that any age effects on memory will be magnified if storage or recall occurs *under dual* task conditions.

A caution is in order. Logically, one could extend a "secondary memory" study to recall intervals of days, months, or even years, but in practice the interval between information presentation and retrieval is usually on the order of five to fifty minutes. Although Psychology texts and review articles freely generalize from the laboratory studies to field situations involving much longer time intervals, there is surprisingly little evidence supporting the generalization. Experiments by Nelson (1967) suggest that the same laws of memory do apply over a wide range of learning-recall intervals. The data is quite sparse, though, and more studies are needed before generalization from laboratory to field can be said to be more than a statement of faith.

MEANINGFUL MEMORY

All of the memory experiments reviewed thus far the participant must remember information that is of little personal relevance. The paired-associates task is a good example. Participants are asked to learn new, arbitrary associations between items. Often the items are nonsense materials or words with low semantic association. The reason for using such material is that psychologists want to study "pure" learning in controlled situations, where the experimenter can control the participants' exposure to the information to be learned.

One approach to the study of meaningful learning is simply to repeat the design of conventional learning and memory experiments, using meaningful material. Suppose that one wished to establish memory span for linguistically organized "chunks" instead of for arbitrary lists of nonsense syllables. A generalization of a memory span study is to determine the longest sentence that can be recalled verbaitm. Sentences of ten or more words can be recalled perfectly. This is considerably beyond the average memory span for unrelated words. The usual explanation is that meaningful material is organized into logically coherent, multi-word units

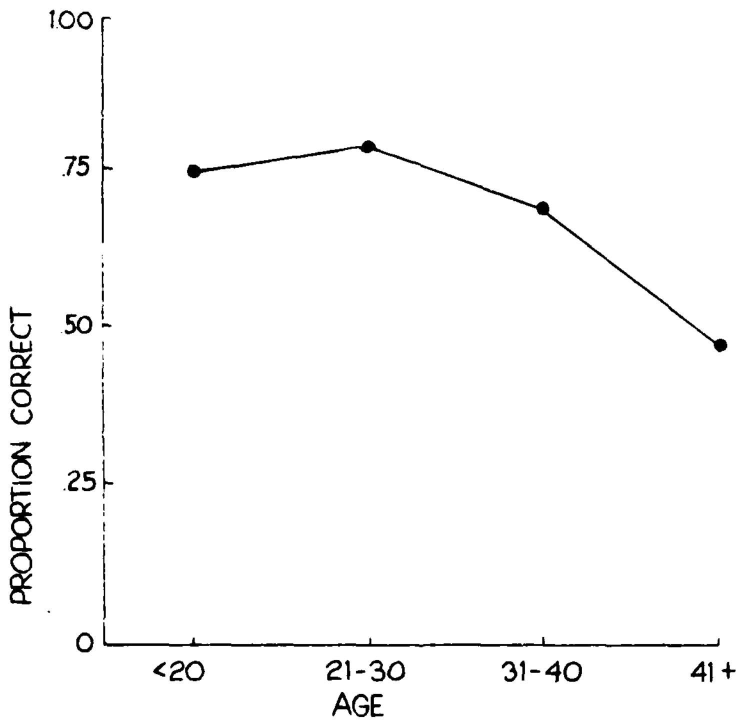

Figure 37. Accuracy of Recognition of a visual matrix of "+" figures. Hunt and Lansman, 1981. ("Hard" condition.)

which then form the unit of memory. For instance, the sentence

"The dog chased the gray cat up the tree"

contains three propositions:

(1) The dog chased the cat.

(2) The cat was chased up a tree.

(3) The cat was gray.

Kintsch and Keenan (1973) have presented evidence indicating that the propositions within a sentence, rather than the sentence itself, are probably the units of memory for prose. More generally, as word strings are moved closer and closer to the structure of sentences (and thus forced into more and more propositional units) people at all ages recall more words from the strings (Craik and Massani, 1966).

As people examine a connected, coherent discourse they begin to construct a propositional network that relates the statements in one sentence to the statements of another. The recall scheme for normal prose is not to attempt to recall the original sentences verbatim, but rather to reconstruct sentences from one's memory of the propositional structure of the to-be-remembered passage (Kintsch, 1974). Studies of prose comprehension are relatively new, and have usually involved contrasts between people in their 20s and 60s, rather than an examination of the full age range. The studies that have been done (Cohen, 1979, 1981; Taub, 1976; Light, Zelinski, and Moore, Note 10) all indicate that there is little age-related loss in the ability to recall propositions, providing that they are made explicit in the text, as were all the propositions in the example sentences given above. It has been found, however, that elderly people are less likely to fill out a propositional structure by constructing propositions that would be inferred from a combination of the propositions in the text and real world knowledge. Continuing with the dog-cat example,

The dog frightened the cat

would be an example of a proposition that could be inferred from the sentences presented previously, although it was not stated in any one of them. The implications of this finding will be considered in more detail in the section on problem solving.

In summary, young adults certainly have a slight advantage over elderly adults in comprehending verbal messages that are presented in a laboratory setting. Whether they have the same advantage over adults in the 40-60 age range is not clear.

Whenever we deal with people we make assumptions about what they know of the world. To what extent are there age-related trends in the availability of different types of "real world" information? Informal reasoning leads us to expect an "inverted U" function relating real world knowledge to chronological age. There is the obvious truism that the longer you live the more experience you have with the world. On the other hand, there is good reason to believe that at some point, and certainly in advanced old age, the efficiency of the learning process declines. Popular fable has it that the elderly retain clear memories of the distant past but are less able to store information about recent events. This is seen in extreme form in certain types of senile dementia, including the premature aging represented by Alzheimer's disease (Gaitz, 1977). Do subclinical manifestations of a resistance to learning begin to appear in the 40s and 50s?

The evidence on this question is quite encouraging. Several studies have shown that older people are, if anything, more aware of general world events than younger people. This seems to be true at least up to age 60. Warrington and her associates (Warrington and Silberstein, 1979; Warrington and Sanders, 1971) found that people in their 40s and 50s knew more about events that had occurred during the past year than did English senior high school students. Lachman and Lachman (1980) found similar results in a study that compared people over 40 to currently enrolled college students, as did Perlmutter (1978), comparing people in the 20s to those in their 60s. It is worth noting that the effects of education appear to be much greater than the effects of age in studies of this sort.

As there is no evidence for a diminished capacity to learn meaningful material during the working years, it is hardly surprising to find that the possession of more knowledge translates directly into better performance in one's field of expertise. In fact, the difference between skilled and average or novice practicioners in intellectually demanding fields is closely related to the amount of relevant knowledge that the expert possesses, rather than any apparent innate skill at problem solving. This has been illustrated by studies of information processing in medicine (Pople, 1977). Experienced internists appear to be fine diagnosticians, not because they are better logicians than less experienced physicians, but because they know a great deal more about the relationship between overt symptoms and underlying disease processes. Similar results have been obtained in the analysis of expert performance in other fields (e.g., Larkin et al., 1980).

Knowledge about one's field of expertise, and for that matter most real world knowledge, is semantic knowledge, i.e., timeless facts that do not refer to personally experienced events. Tulving (1972) has argued that there is a psychological distinction between episodic and semantic knowledge. This distinction is supported in the aging literature; it appears that semantic memory is unusually resistant to age. One of the most reliable findings in the literature on aging and psychometric test performance is that vocabulary scores, a rough measure of knowledge about language, either increase or remain stable until beyond age 60 (Botwinick, 1977). Unfortunately virtually all studies demonstrating the strength of semantic knowledge over the life span are based upon studies of the semantic knowledge embodied in language. But what about information about non-linguistic relations -- for example, principles of machinery operation or procedures. In particular, what about the ability to incorporate changing information about principles, something that occurs continually as technology changes? It is not at all clear that results from studies of the retention of language information can be extrapolated to situations involving memory for non-linguistic information, because language seems to hold a special place in memory, even at the neuroanatomical level (Walsh, 1976). There appears to be almost no information on this important practical question.

A great many of the results on the relation in age and memory have been illustrated in a single study by Lachman, Lachman, and Taylor (1981). They tested memory for facts in middle aged and young schoolteachers, using both a multiple choice and an open ended questionairre format. The older teachers were either equal or superior to the younger ones regardless of type of format. Younger subjects were superior to older ones on memory tests that required the continuous maintainence of information in working memory They were also faster, but not more accurate, in either recalling information from long term memory or drawing inferences from that information. Thus the Lachman et al. study provides, in one report, a good summary of many other studies of memory capabilities over the working years. Other things being equal, older people recall as much (or more) information than younger people. Youth's superiority appears only if there are time pressures, or if it is necessary to keep track of new information for a brief period of time.

The results from studies of memory for meaningful information paint an encouraging picture for any employer considering the use of an older work force. The laboratory picture of deficiencies in learning and memory beginning in the 40s almost certainly overstates the situation. Indeed, there is some reason to believe that older personnel would be superior in recalling meaningful material, providing that recall was required in a situation that did not contain distractions, and that did not place time pressure upon responding.

9. PROBLEM SOLVING

"Problem solving" could refer to almost any cognitive behavior. Following a distinction that is based more on logic than on psychology, problem solving is usually divided into studies of deductive and inductive reasoning. In deductive reasoning one draws conclusions from known facts. In inductive reasoning general rules are abstracted from an examination of specific cases. These definitions are content free; one could classify problems as inductive or deductive regardless of whether they dealt with fields as disparate as physics and medicine. From the time of Aristotle, people who think about thinking have hoped to find rules that describe people's thought, regardless of the content of the problem being solved. George Boole's classic book on binary logic was titled "The Laws of Thought". More recently, during the 1960s there was a spate of work on Bayesian logic as a general theory of human inductive reasoning.

In spite of these historic precedents, the search for a general theory of human problem solving may be doomed to failure. Variations in the content of problems have been shown to exert a powerful influence on problem solving (Wason and Johnson-Laird, 1972). Newell and Simon (1972), in a book that has set the focus for much modern problem solving research, state unequivocally that a person's reasoning will be powerfully influenced by their experience with the material being reasoned about. It is probably unreasonable to assume that there is a general "Psycho-logic", and therefore hardly fruitful to ask how logical reasoning, in general, changes with age. For instance, the difficulty solving of multiple digit addition problems is directly related to the demands that a problem puts on working memory for the storage of intermediate computations (Hitch, 1978). Since there seems to be little, if any, drop in the storage capacity of working memory over the working years, one would not expect to see a drop in accuracy of mental arithmetic with age. On the other hand, there is an age-related reduction in the speed with which material in working memory can be accessed. To make things still more complicated, the extent to which an arithmetic problem makes demands on working memory will depend on the algorithm that a person uses for mental addition. How, then, is one to predict what age effects should be "in general", without knowing the individual's approach to the problem at hand?

Even though individual problem solving strategies can alter the attentional demands of a problem, thinking about problem solving as a demand for mental resources does provide a framework for expecting orderly relations between age and performance on complex reasoning tasks. In particular, problem solving should be more difficult with advanced age when (a) rapid mental computations are required, (b) the problem makes demands upon working memory in such a way that the memory task must be executed as a "dual task", coincidentally with other aspects of problem solving, and (c) the effects of prior learning can be disregarded. The last point is important, because it addresses the question of how efficiently one's mental tools are used. As the extent of prior learning is difficult to document, most psychological studies have tried to avoid the issue, by presenting people with unfamiliar problems. The argument for doing so is that the psychologist wants to determine the covariation between the extent of a person's mental resources and the effectiveness of their problem solving, without having to worry about individual differences in experience. While this is a reasonable scientific goal, it limits the generalization of laboratory studies to field conditions. In the field problems are solved by people who have the background to solve them.

In reviewing the field we shall maintain the classic distinction between inductive and deductive reasoning. In discussing a particular type of problem solving, we shall use the attention deficit hypothesis as a device for organizing the data.

INDUCTIVE REASONING

A popular method of studying inductive reasoning is the concept identification paradigm, in which a person is shown exemplars and non-exemplars of a class of items, and asked to state a general rule for class membership. The items used are typically meaningless forms, such as letter strings or abstract geometric designs. Concept identification problems are described in terms of the information processing characteristics they present. The items themselves may vary in the attributes that define them, and the complexity of the rule defining class membership may be varied. In addition, problems may be described in terms of the size of working memory required to hold enough information to define an answer (Hunt, 1962).

Brinley, Jovick, and McLaughlin (1974) observed age effects in a concept identification study using letter string stimuli. Each problem consisted of the presentation of three letter strings, each labeled with either a "+" or a "-". The task was to define the rule used to assign a string to the "+" or "-" category. To illustrate, one of the problems contained the strings

AB	ab	+
AB	b	-
B	a	+

The rule for this problem is that the label "+" is assigned to all strings containing the symbol "a". Problems were made either hard or difficult in a variety of ways. In some problems all the strings were presented together, in others the strings were presented one at a time. In other cases the rule for assigning labels was more complex. Some example problems are shown in Figure 36. Small but statistically reliable drops in the number of problems solved were found throughout the age range from 20 to 65.

The Brinley et al. experiment is typical of a large number of studies of concept identification in the elderly. The other studies will not be reviewed, because they all concentrate on the contrast between young and elderly people. The results of these studies are consistent with Brinley et al. conclusion that there is a decrement in inductive reasoning with age. The data presented in our review of Psychometrics also indicates that performance on inductive reasoning tests decreases with age.

Although concept identification studies may be similar to some industrial tasks, such as trouble shooting electric circuits, they are certainly not representative of how we learn "real life" rules for classifying objects into trees, people, airplanes, and what have you. Several theories of how this does occur have been proposed (Johnson-Laird and Wason, 1977), and none of them bear very much resemblance to models of concept identification. To our knowledge, however, studies using the more modern models of how real life categories and rules are formed have not penetrated the literature on aging.

DEDUCTIVE PROBLEM SOLVING

The literature on deductive problem solving resembles that on inductive problem solving in two respects; virtually all studies contrast young and old subjects, and they generally conclude that older subjects show reduced powers of deduction, but that there are wide individual differences. Arenberg (1974) reported one of the few experiments that studied individuals of intermediate age and, unfortunately for our purposes, his youngests subjects were in their 30s, and thus were older than most present servicemen and women. The task Arenberg used is of interest because it was designed to resemble a problem in trouble shooting faulty electrical equipment. The problem could be solved by deducing how the lamps must be connected, given observations of the sequences in which they could be turned on and off. Efficiency was measured by the number of sequences that people had to observe before they could state the correct circuit. Groups of middle and upper class males were tested twice, with an intervening period of several years. Subjects in their thirties were more efficient than those in their sixties (there were further declines in the 70s, that are not of concern here). An analysis of individual steps in problem solving showed that the decrease in effeciency was largely due to an increase in the number of non-informative steps taken while testing solutions. This is a typical finding in studies of deductive reasoning. Having formed a hypothesis, people seek information that will confirm the hypothesis in old situations, rather than testing it in new situations (Mynatt, Doherty, and Tweeney, 1977).

Arenberg's study is of interest because of the face validity of the task, and because he was able to say something about the nature of the age-related change in problem solving. A frequent comment about aging is that people become more cautious, which

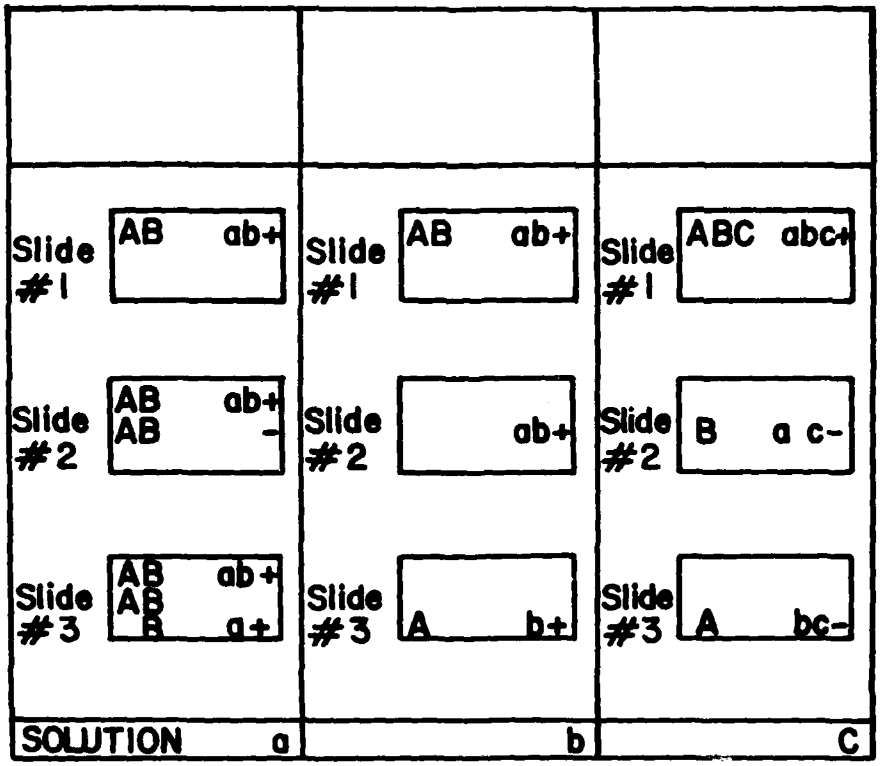

Figure 38. Examples of concept identification problems.

does describe the problem solving behavior of Arenberg's participants. To complete the picture, Arenberg's design should be extended to studies of changes in problem solving behavior over the 20-40 age range.

We earlier raised a question about the generalizability of results based upon laboratory tasks, pointing out that we would expect older, more experienced individuals to do better on problems that were meaningful to them. This does not mean that making a problem meaningful will necessarily make it immune to age-related declines in performance. Two studies have located age differences in reasoning with familiar material. Friend and Zubek (1958) gave the Watson-Glaser Critical Thinking Appraisal test to a sample of over 450 people of widely varying ages and educational backgrounds. This test presents people with paragraphs stating plausible situations. The person is then asked either to a) determine the plausibility of conclusions drawn from the information in the paragraph, b) to recognize the assumptions behind the arguments presented, c) to use logic and weigh the evidence for different conclusions about the situation described, or d) to evaluate the logical coherence of an argument for or against a proposition stated in the text. Friend and Zubek's results are shown in Figure 39. Test scores increased sharply from adolescence to the 20's, peaked in the 20-40 interval, and declined from the 40's onward.

The results in Figure 39 show greater age effects on reasoning ability than is typically found, so a word of caution is in order. The Friend and Zubek study, though large, was a cross-sectional study. As such, it was subject to a confounding of cohort and age effects (see Section 2). In particular, improvement in educational practices in Canada (the site of the Friend and Zubek study) over the period 1920-1955 could have produced a cohort effect that would have been confounded with age effects.

Friend and Zubek's results conflict with those of Lachman, Lachman, and Taylor (1981), who found that older (50s) and younger subjects had virtually an equivalent ability to recall real world facts. Lachman et al. went on to ask their subjects to draw inferences based upon these facts. Some of the inference problems were quite difficult. An example is

"What horror story character would starve to death in Northern Sweden in the Summer?"

(Answer. Dracula, because the sun never sets. The respondent must recall facts about Dracula and about the Arctic Circle, then draw inferences from those facts.)

Lachman et al. found no differences between older and younger subjects in their ability to draw such inferences.

While Lachman et al. also used a cross-sectional design, their subjects were public school teachers, a group specifically chosen for study because the requirements for entry into this profession had not changed markedly over the time period of interest. Lachman et al. hoped that this would reduce cohort effects due to educational differences. Another difference is that the Lachman et al. subjects were better educated than the more heterogeneous group studied by Friend and Zubek. Several authorities have claimed that people who are more cognitive capable as young adults will be more resistant to aging. The topic is further developed in Section 10.

REASONING AND LANGUAGE COMPREHENSION

Comprehending language is not normally thought of as a problem solving task, but it is one. It is not possible to understand normal discourse unless one draws inferences that go beyond the explicit propositions in an utterance. Consider the statement

"A burning cigarette was carelessly discarded. The fire destroyed thousands of acres of virgin forest."

This statement contains four explicit propositions:

The cigarette was burning.

The cigarette was discarded.

The fire destroyed thousands of acres of forest.

The forest was a virgin forest.

In addition the statement contains an implicit proposition,

The cigarette started a fire.

The implicit proposition must be deduced by combining explicit propositions and real world knowledge. For brevity we shall refer to comprehension inferences. Speakers and writers normally assume that listeners and readers will make comprehension inferences. Indeed, it is quite hard to communicate so precisely that comprehension inferences need not be made. Because these unconscious inferences are so important to the communication process, any weakness in drawing them could have serious consequences if people are involved in situations in which they have to understand and respond to verbal or written messages. For this reason a report of age related weakness in comprehension inference (Cohen, 1981) is of considerable interest. Although this study was based on a contrast between young (20s) and old

(65+) subjects, it will be discussed in detail because of its implications,

Cohen had old and young people read several texts such as the one in the "cigarette and forest" illustration just given. After all the texts had been presented Cohen tested for recall of implicit and explicit propositions. Younger subjects recalled both types of propositions equally well (87% accuracy overall), while older subjects did slightly worse on recall of explicit propositions (81%) and much worse (58%) on recall of implicit propositions. Cohen pointed that in normal communication a listener will simultaneously be involved in comprehension inference, based on propositions already presented, and in detecting the propositions underlying the text currently being presented. Thus normal speech comprehension can be looked upon as a special type of dual task. Reading for comprehension should therefore be easier than listening, because a reader can "turn off " the current input while completing a comprehension inference, while a listener cannot. Cohen pointed out that this probably does not matter for young people, who can carry out comprehension inferences fast enough to keep up with a person who is talking at a normal conversational rate. This might not be the case for the elderly, because of their slower rate of mental computation. To test this hypothesis, Cohen had young and old subjects recall the propositions presented in either written or spoken text. The mode of input made no difference for the young subjects. The older subjects found clearly spoken text more difficult to comprehend, even though Cohen took pains to ensure that the acoustic signal was strong enough so that the comprehension of individual words was not a problem.

Cohen's results can be viewed as an inevitable consequence of the slowing of mental processes with age. If this is true, slowing is having a consequence on a very important function, the ability to understand speech. At a theoretical level, this suggests a revision of the psychometrician's "Classic aging hypothesis", that as we age verbal abilities are retained but non-verbal abilities drop out. The evidence for the classic aging hypothesis was gathered in experiments using "verbal comprehension" tests that often did not distinguish between understanding for implicit and explicit propositions. Elsewhere Cohen (1979) has argued that these tests also failed to examine linguistic situations in which the speed of working memory processes was crucial. An example is the resolution of anaphoric references, e.g. establishing a reference to "she" when it occurs in a sentence. Cohen found age-related performance decits in resolving anaphoric references and in other attention demanding aspects of comprehension. To the extent that Cohen's results are generalizable, psychologists may be forced to conclude that there is a greater drop in verbal comprehension in old age than was previously believed to occur.

More information is needed about the parameters of the phenomenon Cohen has reported. We need to know what the relation is between age and th extent of loss of comprehension inference and how this relation is affected by other characteristics of the individual and the situation. The subjects in Cohen's 1981 study were all British university graduates. In her 1979 study two educational levels were considered (university graduate-professional vs. British Leaving Certificate levels, roughly equivalent to U.S. technical high school graduates), and marked effects were found of educational level as well as age. Unfortunately other incomparabilities between the two groups make it inadvisable to consider age x education interactions. Still more important, we are quite without any data concerning changes in comprehension inference in the 20-60 range. If Cohen is correct in assigning the deficit in comprehension to a slowing in the rate at which older people process information, then drops in comprehension inference should begin to appear during the working years. The drop should be greatest whenever comprehension inference had to take place in a dual task situation, or in a situation that was already attention demanding. For example, if a communication were to be received over a noisy channel, such as a loudspeaker in an airport, comprehension inference should suffer. We already know that as people age, the perception of individual words in noise becomes more difficult. Comprehension inference might be even more sensitive to age under undesirable conditions of communication. These are speculations with both theoretical and practical significance. It would be highly desirable to investigate the phenomena reported by Cohen in considerably more detail.

SUMMARY

The data on age-related changes in reasoning and complex problem solving are unfortunately sparse. In this area, even more than in the literature on aging in general, investigators have concentrated on comparisons between "old" and "young", with little attention to the 40 year interval between 20 and 60. Those studies that have been done of people in their working years suggest that there are age sensitive changes in reasoning. Furthermore, these changes may bear a sensible relation to changes in more elementary information processing capacities. To answer this question we need studies in which adults of varying ages take part both in experiments on elementary functions, such as memory and motor decision making, and in experiments on inductive and deductive problem solving.

The report of a drop in the subtler aspects of speech comprehension with age is extremely interesting, for both practical and theoretical reasons. Further study is clearly in order. Apart from the study of speech comprehension, a general criticism can be leveled against the research that has been done on problem solving. Are the right problems being studied? Why are we interested in how people solve novel, made up problems, when in practice they deal largely with the sort of problem they have been trained to solve? This criticism can also be made of literature on memory and aging. The criticism is amplified upon in the next section.

10. A CRITICISM OF THE LITERATURE ON LEARNING, MEMORY, AND PROBLEM SOLVING

Over the working years adults gradually "think more slowly." The loss in speed of mental processing is continuous throughout the working years. An individual is unlikely to notice the effect of cognitive slowing until the late 40s, and not even then for some tasks and people, but on a population basis effects are probably evident by the 40s. While the evidence for slowing is clear, the evidence for a drop in accuracy in mental processes during the working years is much weaker. Should we then conclude that people are progressively less cognitively competent as they age?

The laboratory data are inconclusive. "It depends on the task." If the task requires rapid responding, or if several sources of information must be monitored at once (thus forcing a person to deal with each source quickly) older people probably are less efficient, on the average. If rapid responding is not important, then age is a much less powerful determinant of performance. Taken at face value, these facts about laboratory performance suggest that as people grow older they should be given assignments in which very rapid responding (on the order of milliseconds) is not required, and where it is not necessary to monitor several sources of signals simultaneously. We shall now argue that extrapolations from the laboratory should be done only with caution, because of an important limitation both on the situations studied and on the conceptual thinking that lead to their development.

The point has repeatedly been made that the experimental literature offers no way to allow for the benefits of experience. Virtually all adult learning and problem solving builds upon prior knowledge. Any reasonable extrapolation from laboratory to field performance must take this into account. It is not at all clear, though, just how experience is to be taken into account. In order to do so one must have a detailed conceptualization of how prior knowledge influences of incorporation of new information into our memories. Simply saying "experience counts" is not enough.

In a paper that has had a major influence on Cognitive Science studies, Marvin Minsky (1975) argued for the concept of "frames" of knowledge. Minsky described our minds as being composed of frames that describe prototype situations. When we encounter a new situation, we decide what frame is appropriate and use it to organize newly presented information. To repeat a frequently cited example, we have a frame for "eating out", and our experience with any one restaurant meal must be fit into that frame. Other authors in the Cognitive Science field have used other terminology, such as "scripts" (Schank and Abelson, 1977) or "schemata" (Rumelhart and Norman, 1975) and, to be fair to psychologists, the basic ideas are made quite specific in Bartlett's (generally ignored) analysis of thinking (Bartlett, 1958). The principle is simple. Virtually any complicated experience is to be dealt with by a rather tightly organized, special purpose set of problem solving routines that have been created as a result of our own personal histories. These routines tell us what to notice and how to remember it.

The importance of having frames appropriate to the task at hand has been neatly illustrated by contrasts of the behavior of experts and novices (Bhaskar and Simon, 1977; Chase and Simon, 1973; Larkin et al., 1980). The fields studied have ranged from chess to physics problem solving. Although the studies within any one field tend to be rather weak, they all converge on a common conclusion. A good problem solver in a specialty field is a person who has learned how to deal with the problems that are encountered in that field. That techniques have been learned to deal with obvious problem solving situations, such as the standard openings of chess, is hardly surprising. (It is of some interest to find that physicists seem to have "standard openings" to problem analysis that are in many ways similar to the chess master's openings.) Learned frames may apply at the perceptual level as well. Chase and H. Simon (1973) have shown that expert chess players remember more from a single glance at a board position than do novices. Why? Not because they are superior perceivers, for experts and novices are equal in their memory for illegal arrangements of chess pieces. Experts have learned how to look at the board, and how to see patterns of attack and defense. Experts in a field may be partly born, but they are very largely made. It takes time (and aging) to make them.

Rumelhart and Norman (1981) have developed this theme, using the "frame and schema" terminology of Cognitive Science. They claim that very little human adult learning is properly described by the bit by bit shaping of stimulus-response connections that might properly describe the way a dog learns tricks. Even less of human learning is mirrored by the learning of arbitrary connections between unrelated words. Instead, Rumelhart and Norman maintain, when adults learn they learn (a) how to modify the situations in which complex response schemas apply and (b) occasionally they learn whole new schema. If Rumelhart and Norman are correct, then perhaps 90% of the literature on human learning is simply not relevant to the sort of learning that adults do as they maintain their competence in industrial settings.

Describing in detail the Cognitive Science approach to learning would carry us far beyond the scope of this report. The concepts of the field are just now being worked out. Indeed, to an observer of the field they are in a disturbing state of flux, and it is difficult to determine when there has been an advance and when there has been a change of jargon. This situation may be inevitable in a new field. A more serious issue is that the sort of thinking represented by the Cognitive Science approach has hardly touched research on aging. (There is only one, fleeting reference to the approach in the American Psychological Association's collection of papers "Aging in the 80's" (Poon, 1980), although this anthology is supposed to represent research at the leading edge of the field!). Yet it is in the field of human adult learning, especially in industrial settings, that the Cognitive Science view is most likely to be important.

Although we are quite without data, we suggest that the experimental literature presents a bleaker view of the 30-65 period than is warranted. As people grow older they acquire experience. In particular, they acquire experience about their jobs. The importance of learning in industrial settings has been de-emphasized in research on aging, because most of such research has been targeted toward understanding the problems of people in the post-retirement years. For rather different reasons, learning based on prior knowledge is not a topic easily studied using twenty year old college students. One cannot gain a picture of the mental capacities of 40 year olds without considering both age effects and learning effects. Although people undoubtedly are "thinking more slowly" as they move through the 30s, 40s, and 50s, they are also thinking more efficiently about the things they know. Under the age of 60, older drivers have better accident records. Older pilots fly our airlines, and regularly make split second decisions that protect the lives of hundreds of people. Older lawyers defeat younger ones in courtrooms every day. Why? Because the more experienced individuals already have their frames. The younger ones may be quicker, but their frames for responding are not yet built.

On the other hand, frames do not always fit and technologies do change. At some point, probably not far from 30, we may reach our peaks as physical systems. As information processing systems, we peak later, providing that we keep our frames current. Eventually physical deterioration will overwhelm us, but this may take a long time. The first challenge for psychologists is to develop a theory with which to conceptualize the age-experience tradeoff. An orderly experimental program cannot be developed until this is done.

11. INDIVIDUAL DIFFERENCES

Throughout the working years people become increasingly more different from each other in almost every aspect of cognitive performance. To appreciate the size of the change, the reader might glance back at Figure 3, which shows the distribution of scores on the Raven Matrix intelligence test as a function of age (Heron and Chown, 1968), and at Figure 24, which presents similar data for speed of response selection (Robertson-Tcnabo and Årenberg, 1976). Although response selection and non-verbal reasoning are quite different cognitive behaviors, the distributions shown in the two figures are similar. The mean score on each performance measure decreases with age, and the average deviation from the mean increases. In every age group below 70 the number of people exhibiting high levels of performance remains constant. The number of people exhibiting poor performance increases with age.

Why should individual differences increase with age? One reason is simply that increasing age brings with it an increasing disparity in life experience. Eighteen year olds in our society all share a single pervasive experience, a reasonably uniform school system. By the time the same people are in their forties they will have had years of experience in different life situations. This surely must be a major contributor to individual differences in mature adults. There are also some variables that appear to exert a pervasive effect on adult cognition. Three will be discussed here; level of original ability, general health, and exposure to toxic substances, including diet and drug habits. There are obviously many other special influences that contribute to individual differences in a population of older people, such as ocurrences of brain damage due to accident or infection. Such special causes are not not individually widespread enough to warrant extended discussion. In addition, there are genetically inherited (or genetically sensitive) diseases that influence cognition, such as Alzheimer's disease and Huntington's chorea, whose symptoms appear only in people past thirty. These pathologies are of considerable medical interest, but are relatively rare.

INITIAL LEVEL OF ABILITY

The term "initial ability" will be used to refer to performance on conventional psychometric tests of intelligence, taken during or shortly after a person's school years. No stand will be taken as to whether these are predominantly genetically or environmentally determined. Rather, we take the pragmatic view that the scores themselves are a fact, and ask what sort of statistical predictions can be made about adult performance given knowledge the fact.

Before World War I it was widely believed that people who showed unusual talents as youths were likely to be unhealthy and neurotic as they matured. In the 1920s, Lewis Terman and his colleagues initiated a longitudinal study of gifted children demonstrating that the opposite is true. Terman's participants, who generally had intelligence test scores above 140, had exceptional success throughout adult life. Their scores on (predominantly verbal) intelligence tests were consistent and even increased (Kangas and Bradway, 1971; Terman and Oden, 1947). While the logic of Terman's design has been criticized on a number of points, mostly concerning the lack of a control group, the adult lives of his gifted group were so far above the norm that the major conclusion cannot be seriously questioned. Other studies of people of above average mental ability (although usually not so superior as Terman's subjects) have confirmed Terman's findings (Bayley and Oden, 1955; Nisbet, 1957, Owens, 1953, 1966). Such individuals show stable or improved performance levels over the working years. It should be noted, though, that most of the tests used in the studies cited have been heavily weighted toward verbal performance.

A rather different picture is obtained when one examines longitudinal studies that include cases from the average and below average intelligence and Socio-economic status (SES) ranges. Tuddenham, Blumenkrantz, and Wilkin (1968) gave the Army General Classification Test to a group of servicemen who were retiring from the Army after 20 years service. The resulting scores were compared to the veterans' entrance scores. Tuddenham etal.'s sample consisted mainly of petty officers and sergeants. The distribution of test scores at time of original enlistment indicated that they were representative of what would now be classified as Mental Categories II and III -- the groups that are considered to be desirable for enlistment (Cooper, 1977). The AGCT consists of four parts: a verbal test, a spatial performance test, an arithmentic computation test, and a reasoning test. Tuddenham et al. found decline on all four tests, with the largest decline (.25 standard deviation units) on the spatial performance test. This decline was the only one that was statistically reliable. The verbal test showed the least decline (.1 standard deviation units). Considering the fact that all subtests showed a small decline in an age interval when other longitudinal studies generally find some increment, the presence of small declines in this population seems likely. The Tuddenham et al. study is the only one to report a longitudinal decline in intelligence from the 20's to the 40's. The pattern of the small declines was consistent with the classic aging pattern.

In Section 3 we briefly described the elegantly designed combined cross-sectional and longitudinal sample constructed by Schaie and his co-workers. Schaie's sample was drawn from a large group health cooperative, and can be considered to be intermediate between the college-trained, upper middle class and gifted populations studied by Terman and his followers, and the military group studied by Tuddenham and associates. Hertzog (1979) conducted a detailed reanalysis of Schaie's data, using multivariate statistical techniques that were not available when the data was collected. He formed a general intelligence factor (G) from the Thurstone Primary Mental Abilities (PMA) subtests, and used a longitudinal factor analysis to examine the consistency of individual differences over three test occasions (14 years of longitudinal aging). Individual differences in G were surprisingly constant over the working years, with correlations of .9 or greater between occasions. There was also an increase in G variance, beginning in middle age and becoming more pronounced past 60. This is consistent with the proposition that there is a "fanning" of scores over age; people at the higher levels maintaining or even increasing their scores, while people at lower levels showing continually decreased performance. It should be noted, though, that there are other effects that could have given rise to Hertzog's observations (e.g., interactions of practice effects with initial ability levels). Consistent with Schaie's observations of the raw PMA scores, Hertzog's analysis found no longitudinal decrease in mean scores on G over the working years. Age group means increased longitudinally through the 20s and were constant until about age 55. The increases in variance about this pattern of means suggests that some, but not all of the 40 to 60 year old participants were declining in intelligence -- while the high correlations between occasions indicated that those individuals who were declining were predominately from the lower levels of initial ability.

Taken all together, these studies present a surprisingly consistent result. The pattern of change in cognitive performance varies with the initial characteristics of the sample. Studies of people of high initial ability, and generally high SES, (Terman, Bayley and Oden, Nisbet, and Owen studies) show constancy or improvement over the working years. Schaie's study, which dealt with people reasonably representative of the more stable elements of the Seattle area (i.e. people who remained affiliated with the same health maintainence organization for fifteen years) showed constancy. Tuddenham et al.'s study of 20-year retirees from the military indicated a small decline. Note that there are no studies that have followed a below average population comparable to Mental Category IV. The results from other ability level groups raise the possibility that the lower ability individuals would show the greatest age-related declines during the working years.

Longitudinal studies of aging have a heavy bias toward studying the stable, relatively prosperous elements of our society. It appears that such a bias would lead one to underestimate the size and perhaps the nature of decrements in intelligence test performance, especially at the lower ends of the scale. Given the characteristics of the current military force, which appears to be increasingly biased toward recruitment of personnel in Armed Forces Qualification Test categories III and IV, it would be highly advisable to obtain more information about cognitive change with age in populations with initially low test scores. More is needed than simple observation, we need to know why the decline occurs. For instance, "disuse of cognitive skills" has been proposed as one explanation. Individuals of higher initial ability are thought to occupy positions in society that lead to their continued use of problem solving skills, while individuals of lower ability may not exercise skills similar to test taking skills in everyday life (Blum and Jarvik, 1974). If this is the case, and if the lowered test scores for "low scoring adults" do not reflect their on-the-job performance (broadly evaluated), then there is little cause for concern. On the other hand, if the lowered test scores reflect the influence of life style variables (health habits, drug use, responses to stress, etc.) that are actually producing sub-clinical brain damage, then concern would be warranted.

GENERAL HEALTH STATUS

Health factors interact with aging and cognition more strongly than is generally realized (Eisdorfer and Wilkie, 1977). Consider speed of response selection (CRT), which we have previously shown to be sensitive to age. One of the consistent findings in the gerontological literature is that poor health produces greater slowing of CRT than is found in samples of healthy older individuals (Birren, 1965; Birren, Woods, and Williams, 1980; Eisdorfer and Wilkie, 1977).

Choice reaction time is particularly sensitive to cardiovascular disease, a class of physiological pathologies that generally increase in frequency with age, but are also correlated with a person's choice of life style. In the extreme, hypertension can lead to stroke, which is obviously not good for cognition. Much finer effects can also be shown. Spieth (1965) studied the effects of hypertension and other cardiovascular diseases on a group of pilots (military and civilian) and air traffic controllers. He gave a battery of psychological tasks at the time of the annual medical certification. Men between ages 35 and 59 participated in the study. As would be expected, most of these individuals (338 out of 473) were found to be in excellent health. Others, however, were diagnosed as having minor to severe cardiovascular disease, including hypertension, arteriosclerosis, coronary heart disease, and cerebrovascular disease. Spieth's psychological measures included a 10 choice RT task, the WAIS Digit Symbol Substitution and Block Design subtests, the Halstead Tactual Performance Test, and the Reitan Trail Making Test. Figure 40 shows the distribution of pilots and traffic controllers

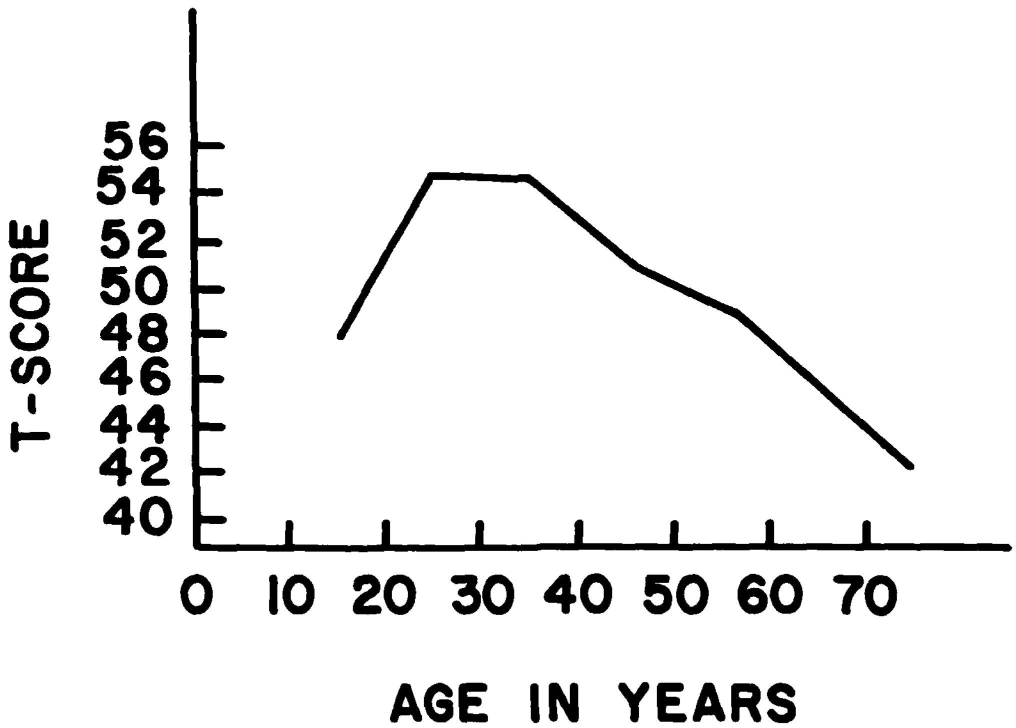

Figure 39. Changes in critical thinking test scores with age. (Friend and Zubek, 1958).

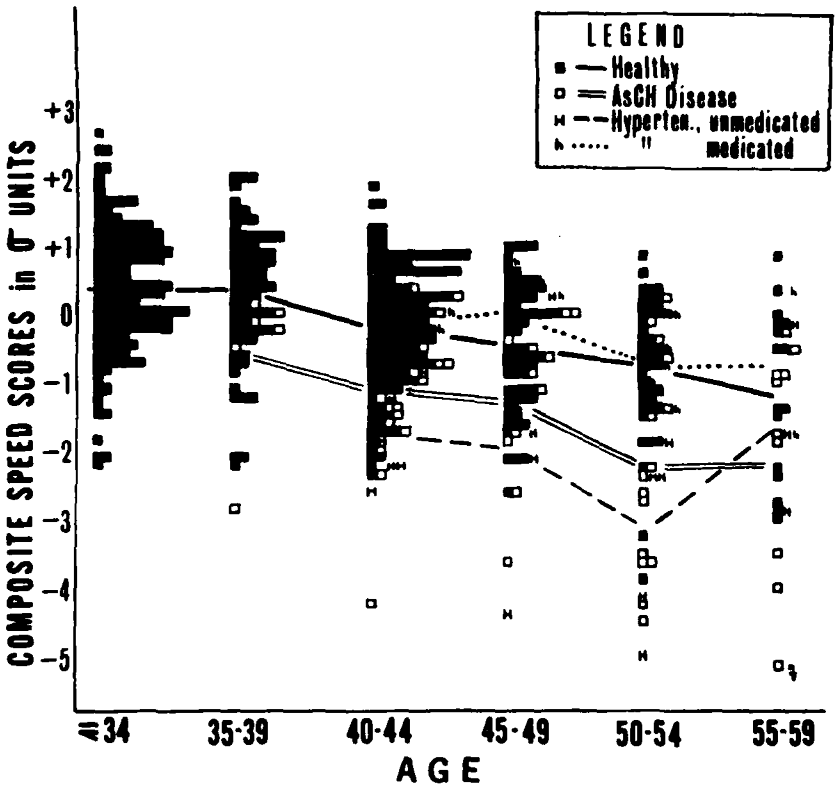

Figure 40. Speed of choice reaction as a function of age and cardiovascular status. Data from pilots. Hypertension is at low clinical level. (Spieth, 1965).

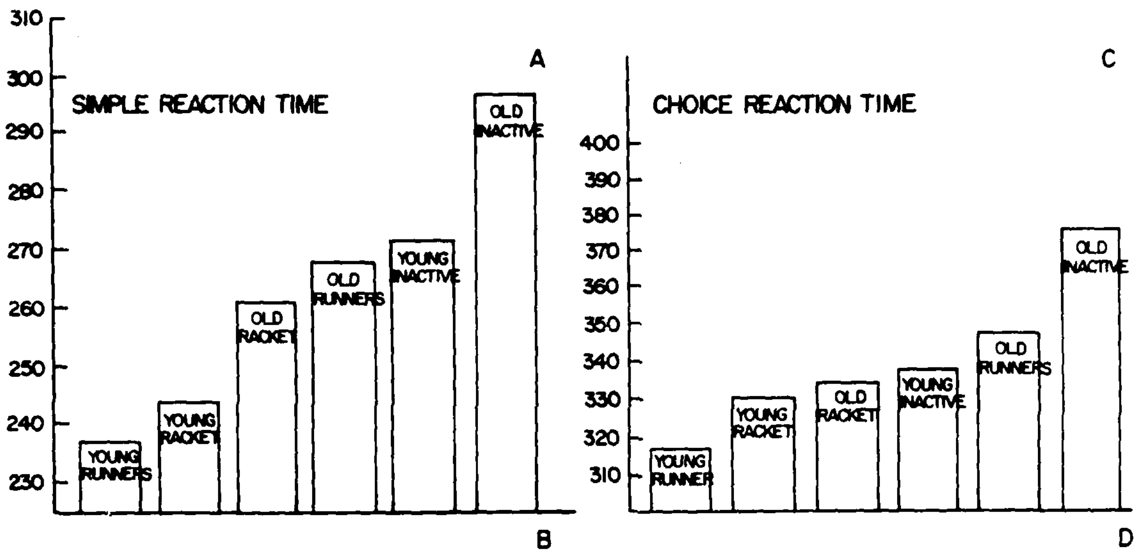

Figure 41. Reaction time as a function of age and physical activity (racket sports, runners, inactive. Young - 20s, Old - 50s.) (Spirduso, 1980).

on a composite speed measure (constructed from the RT task, the Digit Symbol Substitution test, and the Trail Making Test). Note that, in general, individuals with evidence of vascular disease (with the exception of medicated hypertensives) score lower on the speed measure than healthy individuals. The means suggest that the effect is additive with age. However, note that the range of scores for the diseased individuals increases dramatically from age 40 to 60, such that some diseased individuals are markedly slower than their healthy counterparts. This finding probably reflects the fact that there are individual differences in the severity of disease, and consequently, disease effects. Spieth's data therefore suggest that cardiovascular pathology exacerbates any normative slowing in cognitive performance seen over the working years.

One should not misinterpret Spieth's findings about little deficit in medicated hypertensives -- their relatively good performance might have been specific to a mild form of "essential" or benign hypertension. Light (1978) has reported data which indicate that medicated renal hypertensives (hypertension secondary to kidney dysfunction) show evidence of RT slowing during middle age. The cardiovascular effects may also be observed in a slightly more select subpopulation than that studied by Spieth. Szafran (1966) found small, positive correlations (r about .25) between good cardiovascular functioning and choice reaction speed in a sample of commercial pilots. Although the size of this effect is small, it is important because Szafran's middle aged pilots were much healthier than the general population. One would expect to find larger effects in a study of a more representative population.

The same point has been made in a different way by Spirduso's (1980) study of reaction time in people who do or do not participate in athletics, an activity which markedly improves cardiovascular status. Figure 41 presents reaction time as a function of age (20 vs. 50) and participation in sports (inactive, running, racquet sports). The figure certainly supports the maxim, "a sound mind in a sound body." While studies such as this can be faulted for not controlling for selection effects, one still has to be impressed with the fact that the active-inactive contrast is what one would expect by simply extrapolating Spieth's and Szafran's results to a more heterogenous population.

These results offer a good deal of encouragement for the future. Epidemiological trends indicate a slight decrease of hyptertension in the general population (Stallones, 1980). More generally, hypertension is a disease that yields to an individual's choice of dietary habits (including smoking) and leisure time activity. A change in personal habits could provide substantial protection against biological deterioration that would affect mental functioning. The results of the Spieth and Szafran studies suggest that medical screening of the type used for pilots and air traffic controllers would be useful in indicating those individuals at risk for poor work performance because of disease effects.

GENERAL EXPOSURE TO TOXIC ENVIRONMENTS

The literature contains several studies indicating that exposure to toxic substances in the environment may influence cognitive functioning. The nature of the damage suggests that subclinical brain damage may have occurred, for the tests that reveal environmental exposure effects are generally those used in the analysis of the behavioral effects of known brain damage. Atmospheric lead is a good example. It has been shown to be associated with reduced performance of nonverbal reasoning in industrial workers (Valciukas, Lilis, Fischbein, and Selikoff, 1978). Lead has also been implicated as a possible causal agent in behavior disorders in children (Phil and Parkes, 1977). In Section 4 we presented evidence indicating that exposure to unusual noise can cause marked reduction in hearing, with a possible concomitant change in cognitive capacity (due to the increased attentional effort required in verbal comprehension). Such effects are best considered on a case by case basis, coincident with the examination of specific environments, rather than as part of the general topic of cognitive change with age. The results are cited to illustrate a possible source of individual differences in adult cognition.

Dietary influences are somwhat more pervasive. Humans are remarkably immune to long term effects from short term dietary deficiencias, even to the point of near starvation (Stein et al. 1972). While prolonged infant malnutrition may have serious consequences, whatever these might be should be accomplished fact by young adulthood. Thus we do not think that malnutrition, per se, is a serious influence on cognitive performance during the life of a working serviceman.

How an adult's choice of an adequate diet might affect cognition is a matter of some debate. A number of our normal food items, such as coffee, can be shown to have measurable short term effects on cognition. Indeed, coffee (and to a lesser extent, some soft drinks) are taken explicitly for their psychoactive effects. Somewhat surprisingly, we know of no studies of the long term effects of dietary stimulants upon cognition in adults. More recently, attention has been called to the potentially toxic effects of substances added to foods as preservatives or coloring agents. Research to date has focussed on potential clinical effects in children (e.g. Swanson and Kinsbourne, 1980; Weiss et al., 1980). The serious suggestion has been made that long term psychoactive effects of food additives may carry over into adult life (Kimland and Larson, 1980). Nonspecialists tend to dismiss such concerns as "food fads". We would advise an intermediate position. While the evidence gathered to date is not sufficient to warrant any action, we would not find it surprising if subsequent research did show that some of the individual differences in intellectual change in adult life are associated with heavy use of chemically treated foods.

Much the same thing that can be said about foods can also be said about the use of prescription and non-prescription medication. Drugs that are either explicitly psychoactive, as in the case of tranquilizers, and drugs that have substantial psychoactive side effects, such as the various anti-hypertensive agents, are being used more and more widely in medical practice. Use becomes progressively more prevalent as people grow older. We ignore the topic solely because there is little data on long term use of psychoactive drugs in medical practice. While the lack of such data is, in our opinion, a serious deficiency in the public health literature, it is a problem of general concern to society rather than one that is specific to the Armed Services.

ALCOHOL AND DRUG ABUSE

Alcohol use in the military is at least as prevalent as in civilian society. According to Capt. Stuart Brownell, USN, the director of the Navy alcoholism treatment program,

> "about 17% of our total force is afflicted by very serious problem drinking and nearly 10% appear to be chronic problem drinkers in need of immediate help."

Captain Brownell's remarks were made in a press release commenting upon a 1980 Navy self-report survey of alcohol and drug abuse. The same survey indicated that reported problems of chronic alcoholism were concentrated in personnel over 35. While this somewhat contradicts the opinions of medical officers with whom we have discussed the problem, we make no attempt to resolve the issue. The point that is relevant here is that widespread use of alcohol may indeed be a significant source of individual differences in cognitive competence in the services. It is well known that prolonged, excessive use of alcohol can lead to virtual mental incompetence, including incapacitating memory disorders (Korsakoff's syndrome) and a variety of dementias (Parsons and Pignatano, 1977). What is less well known is that there are chronic and perhaps irreversible effects of alcohol abuse upon cognition in people who are well short of permanent commitment to a mental hospital. The chronic effects of alcohol are relevant to the evaluation of changes in mental competence with age, because, as a rough guide, continued alcohol abuse appears to mimic and exacerbate age effects on cognition.

Most of the literature deals with cognition in "the alcoholic." While many definitions of "alcoholics" have been offered, most research work has used the pragmatic definition that an alcoholic is a person who has been committed to an alcoholic treatment program, on either a voluntary or involuntary basis. Note that this is a definition by behavior, rather than by the amount of exposure to the drug.

Mental test performance deficits have been found as much as one year following release from alcohol treatment programs (Long and McLachlan, 1974; Hill, Reyes, Mikhail, and Ayre, 1979; Schau, O'Leary, and Chang, in press). Although alcoholics are not less intelligent than normal subjects overall, they seem to perform less well on the performance scales of the WAIS. They also appear to perform less well on neuropsychological tests intended to measure brain damage (Parsons and Farr, in press). The general picture, then, is similar to that found in the classic aging pattern. Verbal function remains while nonverbal functioning and abstract reasoning performance drops. A catchy way of summarizing the behavioral findings is to think of an alcoholic as a 60 year old who was born 40 years ago! Prior to age 40 the effects of alcoholism are reduced. It is not clear whether this is because the younger alcoholic has had less time to drink or the older alcoholic is more sensitive to the drug. Both statements could be true.

The conclusion that alcoholism leads to brain damage was originally made based on behavioral testing. The development of new physiological measurements has provided evidence leading to the same conclusion. Begleiter, Porjesz, and Chou (1981) report that brain stem evoked potentials are slower in alcoholics, which is consistent with reports of slowed psychomotor functioning. Tomographic studies of alcoholics in the 30-50 age range indicate that there is about a 50% increase in the incidence of signs of neural atrophy after ten years or more of abusive drinking. The comparable figure for control subjects is at most 20% (Bergman, Borg, Hindmarsh, Idestrom, and Mutzell, 1980a,b; Carlen and Wilkinson, 1980; Ron, Acker, and Lishman, 1979).

To what extent is the damage induced by alcoholism reversible by sobriety? Verbal skills are deficient immediately after intoxication, but seem to recover over a period of days or weeks (Goldman and Rosenbaum, 1976). As one would expect, performance on abstract reasoning and perceptual-motor skills, the cognitive functions that are indicators of brain damage, may not recover for months if at all (Kish, Hagan, Woody, and Harvey,1980). These results are typical of others in the literature. However, it should be noted that the data is largely based on studies of alcoholics in their 40s. There is some indication that reversibility is possible for younger alcoholics. As the services have the opportunity of offering treatment to alcoholics at a somewhat younger age than treatment is usually offered, and because the reversibility issue is relevant in decisions concerning the retention of treated alcoholics, further research on reversibility in younger alcoholics would be in order.

About two thirds of the U.S. population uses alcohol (National Institute on Drug Abuse, 1977), while at most 10% could be considered alcoholics. The magnitude of chronic cognitive effects of social drinking is harder to determine than the effect of alcohlism, simply because exposure to the toxic agent is not so great. On the other hand, small effects of social drinking are important because of the prevalence of the habit. The most pessimistic data on the relation between mental functioning and social drinking have been reported by Parker and Noble (1977, 1980). Surveys of quite different populations have shown correlations of between -.3 and -.4 between measures of the amount of alcohol taken when a person drinks and mental test scores. Parker and Noble also report that the relationship between deficit and amount of alcohol drunk is more marked in people past 40. The tests Parker and Noble used are similar to those used to define "fluid intelligence," and abstract reasoning ability, which again agrees with the rough picture of alcohol as mimicking the classic aging pattern. Another interesting aspect of their results is that the important variable seems to be not how much one drinks over a long period of time, but rather the highest level of ethanol concentration reached on the occasion of drinking. Stated less abstractly, "the Saturday night binge is a very bad thing." This is of concern to the Armed Services, because "binge drinking" seems to be fairly widespread. In a recent Department of Defense survey 37% of the respondents reported drinking eight or more drinks a day at least once a month (Alcohol, Drug Abuse, and Mental Health Administration Newsletter, May 1, 1981). This is in excess of the level of drinking reported in Parker and Noble's surveys.

Parker and Noble's results are consistent with more detailed reports that have focussed on "very heavy" social drinkers. This group shows signs of minor brain damage by both behavioral and tomographic criteria (Bergman et al., 1980a; Cala et al., 1978). The tomographic data are particularly interesting because they partially answer a serious problem in the interpretation of studies based on correlations between mental performance and drinking patterns. Drinking patterns and mental test scores are both sensitive to demographic factors. Do people who drink immoderately score low because they drink immoderately, or is it the case that the people who choose to drink heavily are people who would have low mental test scores regardless of their drinking patterns? This question can only be answered by a study of the relation between drinking and test performance, controlled for test performance prior to the advent of serious drinking.

In spite of the prevalent usage of alcohol in our society, there are relatively few published studies similar to those of Parker and Noble. There have been informal reports of failure to replicate their work. The question may revolve around the precise definition of a population. The data from the study of "heavy" social drinkers, combined with Parker and Noble's reports, make it clear that there are some drinking practices of non-alcoholics that are dangerous. These practices seem to be represented fairly heavily in the services. On the other hand, no one would argue that a glass of wine, once a week, produces cognitive damage! Considering the widespread prevalence of drinking habits, it is important to establish more precisely the relation between social consumption of alcohol and detectable cognitive damage.

OTHER DRUGS OF ABUSE

Alcohol is only one of several drugs of abuse. Others, such as the hallucinogens, amphetamines, and cocaine, have received a great deal of publicity. While the effects of these drugs have been and will be studied intensively, there is no evidence at present to regard this as a question that is particularly related to age effects. In the past there has been a tendency for people to move from the drugs in general to use of alcohol as they grow older (National Insitute on Drug Abuse, 1977). Whether this trend will continue cannot be known.

Marijuana is a possible exception to the above statement. The use of marijuana or hashish on a regular basis was reported by 19% of active duty servicemen in the 1980 Defense Department survey. Very little is known about the effects of long term use of marijuana. It can be anticipated that considerable research on this topic will be conducted in the next few years.

CONCLUDING COMMENT

The literature indicates that the large individual differences in aging are by no means random. Level of initial ability, health, and life style -- especially the use of recreational drugs -- all influence cognitive change.

These facts underline the importance of a point that has been made earlier. It can be quite misleading to generalize from age effects observed in one population to anticipated effects in another population. In order to determine how the Armed Services would be affected by an extension of enlistment periods, it will be necessary to measure the interaction between aging, cognition, initial ability, and health factors in populations that are similar to those expected to be in the services in the 1980s.

12. CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

As people age from 20 to 60 the following cognitive changes take place:

1. Verbal and knowledge-related abilities increase. In most situations the improvement in the quality of a worker probably outweighs the disadvantages of age-related decrements in other cognitive functions.

2. Sensory and perceptual capabilities decline markedly from the late thirties onward. The extent of the decline may not be apparent from standard medical examination testing of sensory function.

3. There is a general decrease in the speed of mental functioning that progresses steadily throughout the working years. The evidence that we have reviewed does not support the contention that mental slowing begins to occur only in late middle age, although it may only become apparent on an individual basis at that time.

4. There is an age-related drop in the ability to deal with abstract reasoning situations, especially those involving inductive reasoning. Older workers may find it difficult to solve novel problems, or reason about new situations, especially under time pressure.

5. The literature does not adequately address the issue of whether problem solving using familiar problem solving routines declines during the working years. Nor does it enable us to conclude that there is a decline in memory for newly learned material that is compatible with existing knowledge. To the contrary, the evidence suggests that memory for "meaningful" information is not adversely affected by age. Although the research literature leaves one somewhat optimistic about the maintenance of familiar knowledge and problem solving skills during the working years, more research will be needed to indicate whether technicians and other skilled personnel would be likely to show performance declines between ages 40 and 55.

6. There are large individual differences in all age effects upon cognitive functioning, with the possible exception of the decrement in sensory capacity. Age-related changes in cognitive capacity, or the lack of such changes, reflect individual differences in initial level of ability, in health, and in life style. Maintenance of one's cognitive competence over the working years is positively related to cardiovascular status and

negatively related to excessive use of alcohol. A variety of other more specific determinants of cognitive competence, such as exposure to heavy metals, also have been suggested as a source of individual differences.

RECOMMENDATIONS

The recruitment and retention of older personnel represents a distinct opportunity for the Armed Services. There can be no question that, on the average, men and women in the 30's and 40's are as competent (and in some cases, more competent) to handle most service positions than are people in their late teens or early 20's. On the other hand, there are significant changes in human cognition during the working years which could limit the effectiveness of some personnel on some jobs. We believe the services should develop procedures that would locate those persons who are "at risk" for cognitive changes -- both normal and pathological -- that would affect job performance. The goal would be the development of medical and psychological tests that enable an assessment of "functional age" rather than chronological age. These tests could be incorporated into the annual service medical examinations, and would thus provide an effective means of screening older personnel for performance deficits. Slightly different sets of screening measures might be appropriate for different types of personnel, depending upon the cognitive requirements of their jobs. Such a screening program would minimize the potential for poor job performance resulting from impaired cognitive competence.

Our recommendations are oriented toward the development of these screening procedures. Three classes of specific recommendations will be made. The first deals with immediate policies, that could be executed with very little further study. The second class of recommendations deals with research questions that are closely related to various physical aspects of aging. The final set of recommendations deal with the relationship between psychological factors and "on the job" performance.

Recommendations concerning policy:

1. Physical examinations for personnel over 35 should include extended examination of auditory and visual functions beyond those tests now routine in a physical examination. In particular, tests of dynamic visual acuity and of speech perception in adverse circumstances should be developed. Human engineering research should be conducted to determine how performance on these tests is related to performance in positions where visual or auditory perception is likely to be a limit on effectiveness.

2. Human engineering standards for equipment and operating environments that are perceptually demanding should be re-examined. To what extent have these standards been determined by experiments on younger adults? In some cases further research will be needed to establish appropriate standards.

Recommendations regarding research relating to physiology and cognition:

3. The phenomenon of cognitive slowing has been established in numerous independent experiments. What is not known is whether the cognitive slowing observed in one type of mental performance is the same cognitive slowing observed in another type of performance. A multivariate longitudinal study is required to determine whether mental slowing is or is not a single process that is affected by age. Assuming that a single process is involved, it should be possible to develop an index of cognitive speed that could be included in medical examinations. Choice reaction time and visual masking paradigms are examples of candidate tasks.

4. Research should be conducted to relate behavioral indices of mental slowing to cardiovascular functioning and to chronic exposure to a variety of environmental and dietary agents.

5. Medically related research should be conducted to assess the relationship between cognition and the chronic use of various recreational and prescription drugs, including alcohol. With respect to alcohol, longitudinal studies should be conducted of recovery of mental functioning in individuals who successfully complete treatment for alcoholism. Research is also required on the effect of heavy social use of alcohol in people in the 25-40 age range, as this is the group of most interest to the Armed Services.

6. The services will undoubtedly continue to monitor the use of other recreational drugs by service personnel. In the event that it appears that the pattern of polydrug abuse now observed in younger servicemen continues as the current cohort ages, appropriate studies should be conducted of the cognitive effects of continued heavy use of the most frequently consumed recreational drugs.

Recommendations regarding research on complex cognitive functioning and job performance:

7. Further studies are needed of the relation between measures of mental slowing and more complex tests of psychological functioning, including conventional intelligence tests, and tests of aptitude for specific tasks. These studies should be directed toward populations relevant to the Armed Services, as it has been shown that results are often specific to a particular population. The Reserve forces are suggested as an appropriate group for study.

8. A study is needed that relates performance on age-sensitive tests of cognitive functioning, including both mental slowing and fluid intelligence, to on the job performance in selected occupations representing a spectrum of service duty assignments. The study should be a longitudinal one, in which performance rating changes over a period of years are compared to changes in psychological evaluations. In conducting such a study emphasis should be placed on the study of situations that involve rapid decision making, equipment operation, and spatial skills.

9. Further information is needed on the predicted change in cognitive capacity of individuals who, as young adults, score in the average and below average categories. This study could be combined with the study recommended in paragraph 8, above.

10. More knowledge is needed concerning the relation between age and meaningful learning, i.e. learning that deals with what an individual does in his or her normal life. Such a study should focus on learning in field settings, perhaps associated with the introduction of new technology. It is likely that such research will at first involve detailed case studies and analysis, similar to Norman's (1981) Cognitive Science analysis of minor errors and accidents. Formal experimentation will have to await further conceptualization of the problem.

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